AFWAL-TR-81-2066

(12)

DYNAMIC SEALS FOR ADVANCED HYDRAULIC SYSTEMS

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August 1981

Final Report for Period July 1978 - March 1981

Approved for public release; distribution unlimited

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFWAL-TR-81-2066	2. GOVT ACCESSION NO. AD-A11	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Dynamic Seals for Advanced Hydraulic Systems		5. TYPE OF REPORT & PERIOD COVERED Final Technical Report 1 1978 - 31 March 1981
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Robert B. Olsen		8. CONTRACT OR GRANT NUMBER(s) F33615-78-C-2027
9. PERFORMING ORGANIZATION NAME AND ADDRESS Vought Corporation P. O. Box 225907 Dallas, Texas 75265		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS P.E. 62203F W.U. 31453026
11. CONTROLLING OFFICE NAME AND ADDRESS Aero Propulsion Laboratory (AFWAL/POOS) Air Force Wright Aeronautical Laboratories (AFSC) Wright-Patterson AFB, Ohio 45433		12. REPORT DATE August 1981
		13. NUMBER OF PAGES 306
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

backup ring
two stage rod seals
fly-by-wire actuators
scrapers
single stage rod seals

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of this program was to identify rod seals and scrapers which would give long service life in fly-by-wire (FBW) flight control system actuators.

This project determined a duty cycle spectrum for FBW flight control actuators. Realistic testing of rod seals and scrapers in a -65 to +275°F,

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S/N 0102-LF-014-6601

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

3000 psi, MIL-H-5606 fluid system identified a number of rod seals and scrapers which gave improved performance when compared to a baseline rod seal of MS28774 backups/M83461/1 O-ring or a MS28776M scraper. The rod seal tests evaluated backup rings, single stage, and two stage rod seals of many configurations. Scrapers were tested in an AC coarse test dust environment at 170 to 190°F.

Principle conclusions for rod seals are that two stage unvented rod seals offer a significant reduction in leakage when compared to any single stage rod seal. With the use of a high performance backup ring, O-rings are capable of withstanding the equivalent of 5 years service life in FBW mechanical duty cycles. Single stage rod seals with rubber in contact with the rod leak much less than those with plastic in contact with the rod. Four different two stage rod seal systems were identified which gave no measurable external leakage in tests.

Five plastic and one bronze scraper were tested which allowed less transmission of contaminant to the rod seal than the MS28776M baseline.

PREFACE

This final report was prepared by Vought Corporation, Dallas, Texas, under USAF Contract F33615-78-C-2027. The contract work was performed under Project 31453026 under the direction of Air Force Wright Aeronautical Laboratories, Aero Propulsion Laboratory. The program was administered by Mr. William B. Campbell, Project Engineer, AFWAL/POOS.

In an applied research program of this magnitude, the technical skills and cooperation of many people are required. Mr. G. K. Fling gave technical direction for execution of the program. W. V Brewer performed all typing and word processing. Mr. M. K. Allen designed the test fixture and Mr. J. A. Bird designed the test system hydraulic setups as well as supervised and assisted the technicians in performance of the tests. Principal technicians were Mr. L. C. Cook and Mr. T. Coates. Fabrication of end caps and piston rods was under the supervision of Mr. W. T. McLaughlin. Eleven manufacturers of seals and scrapers participated with recommendations and test samples. Major efforts in time and materials were made by C. E. Conover Co., Greene, Tweed Co., W. S. Shamban Co., Tetrafluor Inc., Dowty Seals Ltd, and Parker Packings. The author wishes to express appreciation to these recognized and others who cooperated.

The discussion of materials or test specimens by brand names or suppliers in this report is in no way to be taken as an endorsement or criticism by the government. In some instances, the items were or may have been subjected to conditions exceeding those recommended. The government incurs no liability or obligation to any supplier from the information included in this report.

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DYNAMIC SEALS FOR ADVANCED HYDRAULIC SYSTEMS

1. INTRODUCTION

External leakage accounts for approximately 96 percent of all primary flight control actuator removals in current aircraft. Relaxed static stability, in aircraft design, causes an increase in actuator activity which demands that better dynamic seals be found.

Fly-By-Wire (FBW) control systems are usually adopted so that the airplane can be designed with relaxed stability. One of the penalties is that increased reliance is placed upon the artificial stabilization system. Also, a fly-by-wire system implies the probable use of a much larger number of electro-hydraulic valves than would be found in a conventional system. Total FBW valve neutral leakage plus leakage of any power valves possibly will cause the system to operate hot. Adequate heat exchanger design and use of elastomers truly compatible with system temperatures will be required.

The FBW actuator is usually a larger, more complex piece of equipment than actuators used in the past. The maintenance man hours required for removal and replacement is expected to be greater than that of conventional actuators. As the complexity increases, the number of seals increase, increasing the probability of leakage. Therefore, sealing improvements are required to meet reliability requirements. With reliable test data which indicates a thermal life of 1000 hours at +275°F for MIL-P-83461 elastomer plus knowledge of endurance spectrum versus flight hours and actual flight hours per year, the time may come when overhaul intervals for hydraulic seals may be predicted and used in life cycle cost studies to establish decision criteria for trade offs of cost of initial manufacture versus cost of overhaul.

Power control actuators have traditionally had manual inputs from the pilot's stick or foot pedals, or by a series electro-hydraulic actuator, which is controlled by selection of auto pilot, stabilization, or control augmentation modes. These flight control actuators would normally be qualified to either 2×10^6 or 5×10^6 cycles depending upon whether they were classified as manual input actuators or autopilot actuators, respectively. Fly-by-wire (FBW) control systems can add to these qualification test requirements by imposing thousands of dither cycles.

Therefore, the goal of this program was to establish and demonstrate improved seal technology, by analysis and test, which will provide long service life actuators for FBW systems. The tasks identified to achieve this goal were:

User Industry Survey
Seal Industry Survey
Fly-By-Wire (FBW) Control System Study
Backup Ring Screening Tests
Scraper Screening Tests
Single Stage Rod Seal Screening Tests
Two Stage Rod Seal Screening Tests
Long Life Tests

All backup rings, scrapers, and seals were selected and tested for application in a 3000 psi, -65 to +275°F, MIL-H-5606 Hydraulic Fluid System. This report covers results of work conducted in the time period 1 July 1978 through 31 March 1981.

2.0 RESULTS OF SURVEYS

2.1 User Industry Survey

In order to gain current information on problems and service experience with a number of seal materials and configurations, a survey was conducted and analyzed. The information gained was considered in the selection of seal candidates.

The survey was mailed to seventeen persons in the aircraft industry who are knowledgeable of seal performance or active in seal design. Two surveys were drafted. One was oriented toward airframe manufacturers and the other toward the airline industry. There were fourteen responses to the survey. A summary of the responses gave these results.

a. Only four responses had conducted tests on scrapers.

b. Nine scraper designs had been used with varying results. MS28776 scrapers were rated good to excellent by 6 responses.

c. Four responses mentioned the imbedment of metal particles and abrasive contamination in TFE seals as a factor in leakage and wear of piston rods.

d. Two stage vented seals were rated good to excellent by all responses.

e. T-seals received good to excellent ratings from nine responses.

f. MIL-G-5514 glands were used exclusively. Modifications mentioned were for control of squeeze, to increase seal/groove occupancy or for installation of special seals.

g. TFE cap seals as a group were rated fair to good.

h. MS28774 backups with MS28775 O-rings were rated fair to good by 10 responses.

i. Airline users reported leakage and elastomer wear/extrusion as predominant evidences of failure at overhaul.

j. Seven bushing materials were used. Aluminum-bronze was mentioned by seven responses.

Appendix A is a compilation of the User Industry Survey Results.

2.2 Seal Industry Survey

Because the temperature, pressure, and fluid requirements of this program are common to a number of aircraft fluid systems in operation with the difference being the endurance spectrum, inputs from the seal industry were sought in order that the widest possible spectrum of materials and configurations might be considered. Also, there were products available for industrial applications which appeared to have potential for aircraft use. Information and recommendations from the seal industry was requested by means of a mini-specification.

The specification was mailed out to nineteen seal manufacturers. Ten responses of literature, catalogues, or direct presentation of candidates were received. Cooperation by the participating vendors was excellent. The candidates were evaluated for potential performance with respect to temperature, wear, installation, producibility, and other factors. Based upon this evaluation, candidates were selected for the screening tests.

2.3 Fly-By-Wire (FBW) Control System Study

With the introduction of production aircraft with FBW control systems, the probability of future aircraft with FBW control systems is increased. The type of mechanical environment actuator seals will be exposed to is not well known nor widely disseminated. The aircraft industry anticipated that the number of cycles seals would see in FBW actuators would be higher than for manual control systems with automatic flight control inputs, but the actual total cycles and the distribution of the percent amplitude was not known. Therefore, a realistic FBW endurance spectrum is needed.

A requirement of this program was to determine a realistic endurance spectrum for actuators in a FBW control system. The spectrum was derived by analyzing data from a number of sources. Flight test data from several aircraft of UHT surface position versus time was ultimately used to determine the spectrum in this report.

The endurance spectrum study was completed and the spectrum, which corresponds to a 4000 hour aircraft life, is as follows:

Percent Stroke	Total Cycles
1.0	3.62×10^7
2.0	3.50×10^6
10.0	2.50×10^5
50.0	4.00×10^4
100.0	1.00×10^4
	40.0×10^6

A cycle is defined as one-half the percentage stroke to retract, the full percentage stroke to extend, and one-half the percentage stroke to retract to the original starting point.

The percent stroke from the data received is defined as the measured stroke divided by the total working stroke from full trailing edge down to full trailing edge up.

An accounting of the data received and its disposition is as shown on Table 1.

The endurance spectrum was derived using the following plan:

1. The data traces of horizontal tail position versus time were analyzed. Each clearly definable movement of the surface was recorded by surface position. The elapsed time for the data was determined.

2. The surface positions were tabulated and the change in positions for each movement was calculated to give a "stroke".

3. The strokes were grouped by magnitude and counted.

4. F16 Mission Profile Data, Table 2, was used to prorate the number of occurrences of each percent of stroke from the elapsed time for the data to the number of occurrences which will occur in 4000 hours of aircraft life using the following formula:

$$K_{4000} = K_{data} \times \frac{4000}{t_{data}}$$

Where K_{4000} = no. of occurrences in a 4000 hour life.

K_{data} = no. of occurrences counted in data.

t_{4000} = total time particular mission profile occurred in 4000 hours.

t_{data} = elapsed time for data counted.

For example, from Table 2, the total time spent out of 4000 hours for landing, take off, or touch-and-go runs is 115.45 hours. From the Fly-By-Wire (FBW) F8 UHT data (Table 4), the number of 1.54 percent strokes in 53.48 minutes of data was 462.

$$K_{4000} = 462 \times \frac{115.45 \text{ hr.}}{53.48 \text{ min}} \times \frac{60 \text{ min}}{\text{hr.}}$$

$K_{4000} = 5.98 \times 10^4$ strokes of a magnitude of 1.54 percent of total stroke

5. Next the total number of accumulated strokes in 4000 hours was calculated by adding the number which resulted from take-off and landing, supersonic flight, subsonic flight, and air-to-ground weapon delivery as shown in the following tabulation.

Mission Profile	t_{data} - sec	Total K_{Data}	$t_{4000\ hr}$ (from Table 2)	Total K_{4000}
Take Off; Land; Touch and Go	3208.8	2479	115.45	3.21×10^5
Supersonic	19	162	207.4	6.37×10^6
Subsonic	16	90	3458.6	70.04×10^6
Air-To-Ground Weapon Delivery	394.8	1508	216.9	2.98×10^6
			3998.4	79.71×10^6

Since, by definition 1 cycle = 2 strokes the total endurance spectrum consists of:

$$79.71 \times 10^6/2 = 39.86 \times 10^6 \approx 40 \times 10^6 \text{ cycles}$$

6. After looking at several methods to determine percentage strokes to be used to constitute the spectrum, an extension of MIL-C-5503C was selected, giving the test-points as 100, 50, 10, 2, and 1 percent of total stroke. The lower limit of 1 percent was established recognizing the increasing difficulty in achieving and repeating a very small stroke. For example, 1 percent of a 2 inch stroke actuator would mean being able to achieve and repeat a $\pm$.01 inch cycle.

7. To determine the total cycles at each test point, the data was divided so that data which included percentage strokes less than or equal to a test point are counted as occurring at the test point. As an example the FBW F16 supersonic data shown below has percentage strokes as low as 0.2 percent. Therefore, all strokes between 0.2 percent and 1.0 percent are counted as 1 percent in the endurance spectrum. Similarly, the percentage strokes occurring above 1 percent up through 2 percent are counted as 2 percent strokes in the endurance spectrum.

	Percent Stroke	Occurrences in 4000 hr. life
	0.2	1.73×10^6
Count as	0.4	1.57×10^6
1 percent in	0.6	1.61×10^6
endurance	0.8	7.46×10^5
spectrum	1.0	1.57×10^5
	1.2	3.54×10^5
Count as	1.4	3.93×10^4
2 percent in	1.6	7.86×10^4
endurance	1.8	7.86×10^4
spectrum	2.0	7.86×10^4

8. The largest stroke seen in the data was 20.85 percent. Since two important test points are 50 and 100 percent of stroke, the difference between 39.89×10^6 and 40×10^6 cycles was filled in by apportioning cycles to the 10, 50 and 100 percent cycles until the total was 40×10^6 cycles.

Table 3 summarizes the adjustment to data and the final spectrum to show pictorally, the adjustments to the observed data.

Tables 4 through 6 give the stroke data used to derive the endurance spectrum.

TABLE 1. ACCOUNT OF ENDURANCE SPECTRUM DATA

DATA	DISPOSITION
1. NASA, FBW F8; touch and go landings, time history of UHT position.	Data analyzed and used to derive the endurance spectrum.
2. F111; air to ground weapon delivery, time history of UHT position.	Data analyzed and used to derive the endurance spectrum. See Note 1 below.
3. F16; supersonic flight, time history of UHT position	Data analyzed and used to derive the endurance spectrum.
4. F16; subsonic flight, time history of UHT position	Data analyzed and used to derive the endurance spectrum.
5. C5; complete endurance spectrum inboard elevator, Active Lift Distribution Control System	Data reviewed but not used (See Note 2). Percentage strokes below 2 percent are not shown.
6. SST (Boeing); complete endurance spectrum, rudder	Data reviewed but not used (See Note 2). Percentage strokes below 2 percent are not shown.
7. F18, complete endurance spectrum flight control actuators	Data reviewed but not used (See Note 2). Percentage strokes below 2 percent are not shown
8. F111, complete endurance spectrum UHT servo input	Data reviewed but not used (See Note 2). Servo valve position does not always correspond to surface position.

Note 1. The F111 pitch system is a high authority command augmentation system and is estimated to be very similar if the F111 was total fly-by-wire.

2. A derived endurance spectrum was supplied by the airframe manufacturer. However, because the data was not actual time history of surface position versus time, it was not possible to incorporate this data into the derivation of the fly-by-wire endurance spectrum for this program.

TABLE 2. F16 MISSION PROFILE DATA

Mission	T.O.; Land Or Touch and Go - Hr.	Subsonic Flt - Hr	A/G Weapon Del - Hr.	Supersonic Flt - Hr.	Total Hours
1. Training - Transition	22.7	371.7	0.0	13.6	408.0
2. Training - Inst. NAV/Refueling	66.7	733.3	0.0	0.0	800.0
3. Training - ACM/ Tactics	26.7	1333.3	0.0	240.0	1600.0
4. Training - A/A Gunnery	18.4	772.8	0.0	18.4	809.6
5. Training - A/G Weapon Deliv.	24.5	417.1	368.0	0.0	809.6
6. Combat - A/A Fighter Sweep	6.8	797.9	0.0	11.3	816.0
7. Combat - A/A Fighter Escort	11.7	783.2	0.0	14.7	809.6
8. Combat - A/A Intercept	24.0	302.4	0.0	76.8	403.2
9. Combat - A/G Close Air Supp.	9.6	323.2	51.2	0.0	384.0
10. Combat - A/G Interdiction	8.8	381.3	14.7	0.0	404.8
11. Ferry	4.3	347.7	0.0	0.0	352.0
12. Funct. Flight Check	6.7	353.3	0.0	40.0	400.0
TOTAL IN 8000 HR	230.9	6917.2	433.9	414.8	7996.8
TOTAL IN 4000 HR	115.45	3458.6	216.95	207.4	3998.4

Note: From this breakdown, time history data from the FBW F-8 was proportioned to the Take Off, Land, or Touch and Go time in 4000 hours. Time history data from the F-16 was proportioned to the Subsonic and Supersonic time in 4000 hours and the F111 pitch system time history data was proportioned to the A/G Weapon Delivery in 4000 hours to determine the total numbers of cycles in 4000 hours.

TABLE 3. SUMMARY OF DATA ADJUSTMENT

	Data - Percent Stroke					
	0 To 1	1 To 2	2 To 10	10 To 50	50 To 100	
Percent Stroke in Spectrum	1	2	10	50	100	
Data - No. Occurrences In 4000 Hrs.						Total
T.O., Land, Touch and Go (FBW F8)	129,266	59,841	125,639	6,347	0	321,093
Supersonic (FBW F16)	5,815,933	550,155	0	0	0	6,366,088
Subsonic (FBW F16)	64,589,355	5,447,295	0	0	0	70,036,650
Air to Ground Weapon Deliv. (F111)	1,982,224	666,676	334,327	0	0	2,983,227
TOTAL OCCURRENCES	72,516,778	6,723,967	459,966	6,347	0	79,707,058
CYCLES = OCCUR/2	36,258,389	3,361,984	229,983	3,174	0	39,853,529
Adjust and Round Off for Final Spectrum	$36.2x10^6$	$3.5x10^6$	$2.5x10^5$	$4.0x10^4$	$1.0x10^4$	$40.0x10^6$

TABLE 4. FBW F8 UHT STROKE DATA
(Take Off, Land, Touch and Go)

PERCENT STROKE	NO. IN 53.48 MIN	NO. IN 115.45 HR
0.77	998	129266
1.54	462	59841
2.32	229	29661
3.09	195	25257
3.86	124	16061
4.63	105	13600
5.40	78	10103
6.18	74	9585
6.95	57	7383
7.72	39	5051
8.49	28	3627
9.27	24	3109
10.04	17	2202
10.81	13	1684
11.58	5	648
12.36	8	1036
13.13	6	777
13.90	1	130
14.67	4	518
15.45	2	259
16.22	2	259
16.99	2	259
17.76	2	259
18.53	0	0
19.31	3	389
20.08	0	0
20.85	1	130
	2479	321093

TABLE 5. FBW F16 UHT STROKE DATA
(Supersonic and Subsonic Flight)

PERCENT STROKE	SUPERSONIC FLIGHT NO. IN 19 SEC	SUPERSONIC FLIGHT NO. IN 207.4 HR	SUBSONIC FLIGHT NO. IN 16 SEC	SUBSONIC FLIGHT NO. IN 3458.6 HR.
0.2	44	1729061	45	35018325
0.4	40	1571874	22	17120070
0.6	41	1611171	6	4669110
0.8	19	746640	6	4669110
1.0	4	157187	4	3112740
1.2	9	353672	4	3112740
1.4	1	39297	1	778185
1.6	2	78594	1	778185
1.8	2	78594	0	0
2.0	0	0	1	778185
2.0	162	6366088	90	70036650

TABLE 6. F111 UHT STROKE DATA
(Air to Ground Weapon Delivery)

Percent Stroke	No. in 6.58 min	No. in 216.95 hr	Percent Stroke	No. in 6.58 min.	No. in 216.9 hr
.055	28	55391	2.458	9	17804
.112	106	209696	2.514	3	5935
.167	69	136500	2.570	7	13848
.223	97	191892	2.626	3	5935
.279	42	83087	2.682	5	9891
.335	86	170131	2.737	4	7913
.391	41	81109	2.793	7	13848
.447	80	158261	2.849	2	3957
.502	31	61326	2.905	5	9891
.558	68	134522	3.017	4	7913
.614	30	59348	3.073	1	1978
.670	64	126609	3.128	3	5935
.726	39	77152	3.185	1	1978
.782	65	128587	3.241	8	15826
.838	32	63305	3.296	1	1978
.893	58	114740	3.352	2	3957
.949	25	49457	3.408	3	5935
1.005	41	81109	3.464	6	11870
1.061	15	29674	3.576	4	7913
1.117	36	71218	3.631	1	1978
1.173	27	53413	3.687	1	1978
1.229	28	55391	3.799	4	7913
1.285	15	29674	3.855	2	3957
1.341	25	49457	3.911	3	5935
1.397	15	29674	3.967	2	3957
1.452	33	65283	4.022	3	5935
1.508	10	19783	4.134	1	1978
1.564	21	41544	4.246	1	1978
1.620	6	11870	4.358	1	1978
1.676	22	43522	4.414	1	1978
1.732	14	27696	4.469	0	0
1.788	14	27696	4.581	2	3957
1.844	6	11870	4.861	1	1978
1.899	17	33631	5.028	1	1978
1.955	10	19783	5.252	1	1978
2.011	23	45500	5.307	1	1978
2.067	2	3957	5.363	1	1978
2.123	17	33631	5.587	2	3957
2.179	7	13848	5.698	2	3957
2.235	12	23739	8.045	1	1978
2.290	5	9891		1508	2983227
2.346	12	23739			
2.402	4	7913			

3. SCREENING TEST RESULTS

3.1 Backup Rings

A total of 30 configurations were tested in four separate tests. Eighteen candidates were tested in the initial backup screening tests, from these 18, eight were included in further evaluation during the scraper screening tests. Two of these candidates, one with an improved material, were evaluated in the Long Life Test. Upon conclusion of the Long Life Tests, 12 additional candidates were tested in the time remaining to determine if trends noted in earlier tests could be confirmed. Test conditions and number of endurance and impulse cycles will be stated prior to each group of backups.

Table 7 tabulates the characteristics evaluated in each backup candidate.

Table 8 summarizes the backup ring screening test results.

Table 9 classifies backup candidates into four categories according to O-ring condition. It shows that six candidates - B3, B8, B9, B20, B23, B22 and B35 allowed no O-ring damage in at least one test.

Unless noted, the following candidates were subjected to 3.17×10^6 cycles dynamic cycling accomplished in blocks which had proportions of cycles in accordance with the FBW endurance spectrum. Oil temperature was 275°F, ambient air was 275°F. The candidates had constant 3000 psig applied during cycling. A total of 78578 impulse cycles of 0 - 4500 psig were applied by application of 4545 cycles after each day's dynamic testing. Conditions for evaluation during the scraper screening tests were the same except box ambient was 170 to 190°F, no impulse pressure cycling was applied, and 3.3×10^6 endurance cycles were accomplished.

TABLE 7. CONCEPTS TESTED IN BACKUP RING SCREENING TESTS

Candidate No.	SINGLE BACKUP CONFIGURATIONS: THICKNESS: Std	HD	Double	ID FIT: Clr	Int	MATERIAL: Unfilled TFE	Filled TFE	Acetal Resin	Polyimide	CONSTRUCTION: Cut	Uncut	Shape	Part No. Ref.
B1	X			X		X				X		Rect	MS28774-214
B9	X			X		X					X	Rect	MS27595-214
B16	X				X	X					X	Rect	CEC5083-214
B17			X		X	X					X	Sqr	CEC5075-214NC
B8		X			X	X					X	Tri	DB12-02-214
B4	X				X		X				X	Rect	CEC5065-214
B21		X			X		X				X	Rect	S33012-214-14
B5			X		X		X				X	Sqr	CEC5062-214NC
B2		X			X		X				X	Rect	S32974-214-18
B15		X			X				X		X	Rect	TF855-214
B3		X			X		X				X	Trap	S32975-214-18
B10		X			X		X				X	Con	TF881-214A
B23		X			X		X				X	Trap	S32975-214-20
B24		X			X		X				X	Rect	CEC5110-214
B25		X			X				X		X	Rect	TF-XXX-2-2
B26		X			X			X			X	Rect	TF-XXX-2-3
B27		X			X				X		X	Trap	TF-XXX-1-2
B28		X			X			X			X	Trap	TF-XXX-1-1
B29		X			X		X				X	Trap	CEC5056C-214
B30		X			X		X				X	Trap	S32975-214-99
B31		X			X			X*			X	Rect	TF-XXX-2-1
B32		X			X		X				X	Rect	TF95A-7214A
B33		X			X		X				X	Rect	TF95-7214-600
B34		X			X		X				X	Rect	TF95A-7214B
B35		X			X		X				X	Trap	S32975-214-19

Abbreviations:
Std - Standard
HD - Heavy Duty
Inr - Inner
Otr - Outer
Cir - Clearance
Int - Interference
Tri - Triangle
Sqr - Square
Rect - Rectangle
Trap - Trapezoid
Con - Concave
*with TFE filler

TABLE 7. CONTINUED

Candidate No.	THICKNESS Std	THICKNESS HD	THICKNESS Double	ID FIT Cl	ID FIT Int	MATERIAL Unfilled TFE	MATERIAL Filled TFE	MATERIAL Acetal Resin	MATERIAL Polyimide	CONSTRUCTION Cut	CONSTRUCTION Uncut	CONSTRUCTION Shape	Part No. Ref.	
	TWO STAGE BACKUP CONFIGURATIONS													
B20 Inr	X			X			X			X		Rect	TF1007-214-3	Inr
B20 Otr	X			X			X			X		Rect	TF1007-214-2	Otr
B18 Inr	X				X	X					X	Rect	CEC5083-214	Inr
B18 Otr	X				X	X					X	Rect	CEC5083-214	Otr
B6 Inr	X				X	X					X	Rect	CEC5083-214	Inr
B6 Otr		X			X				X		X	Rect	TF855-214	Otr
B19 Inr	X				X		X				X	Rect	TF830-214-2	Inr
B19 Otr		X			X				X		X	Rect	TF830-214-1	Otr
B22 Inr		X			X		X				X	Rect	CEC4862-214NC	Inr
B22 Otr		X			X		X				X	Rect	CEC4862-21NC	Otr

Abbreviations: Std - Standard; HD - Heav/ Duty; Inr - Inner; Otr - Outer; Cir - Clearance; Int - Interference; Tri - Triangle; Sqr - Square; Rect - Rectangle; Trap - Trapezoid; Con - Concave

TABLE 8. SUMMARY OF BACKUP RING SCREENING TEST RESULTS

Candidate	CONDITION Backup	O-Ring	Total Leakage drops	No. Mechanical Cycles	Diametral Clearance	Test
B1 (S)	MW	F	8	3.17×10^6	.0038	BS
B1 (A)	MW	G	0	3.17×10^6	.0036	BS
B2 (S)	LW	G	5	3.17×10^6	.0039	BS
B3 (S)	LW	E	0	3.17×10^6	.0033	BS
B4 (S)	MW	F	3	3.17×10^6	.0042	BS
B5 (S)	MW	P	12.4 ml	3.17×10^6	.0042	BS
B6 (S)	SW	P	4	3.17×10^6	.0032	BS
B8 (S)	SW	E	0	3.17×10^6	.0032	BS
B9 (S)	LW	E	0	2.59×10^6	.0025	BS
B10 (S)	MW	P	4	3.17×10^6	.0027	BS
B15 (S)	LW	P	SR	226077	.0030	BS
B16 (S)	SW	F	0	3.17×10^6	.0024	BS
B17 (S)	MW	P	11	3.17×10^6	.0030	BS
B18 (S)	SW	P	LF	1.43×10^6	.0035	BS
B19 (S)	SW	F	0	3.17×10^6	.0033	BS
B20 (S)	LW	E	3	3.17×10^6	.0028	BS
B21 (S)	MW	P	15	2.76×10^6	.0032	BS
B22 (S)	LW	E	4	1.63×10^6	.0035	BS
B3	LW	E	2	3.30×10^6	.0039	SS
B1	LW	G	0	3.30×10^6	.0040	SS
B8	LW	E	2	3.30×10^6	.0034	SS
B20	LW	G	3 ml	3.30×10^6	.0031	SS
B5	LW	P	0.6 ml	3.30×10^6	.0046	SS
B21	MW	P	92.5 ml	3.30×10^6	.0043	SS
B22	LW	E	1	3.30×10^6	.0030	SS
B9	LW	F	2.1 ml	3.30×10^6	.0049	SS
B35 (S)	LW	E	7.95 ml	13.31×10^6	.0030	LL
B35 (A)	SW	F	2.45 ml	13.31×10^6	.0030	LL
B35 (S)	LW	E	0	13.31×10^6	.0029	LL
B22 (S)	SW	F	141.25 ml	13.31×10^6	.0027	LL
B1 (S)	SW	G	217.2 ml	13.31×10^6	.0030	LL

TABLE 8. CONTINUED

Candidate	CONDITION Backup	CONDITION O-Ring	Total Leakage drops	No. Mechanical Cycles	Diametral Clearance	Test
B23 (S)	MW	E	10	3.37×10^6	.0040	AS
B1 (S)	MW	P	LF	2.08×10^6	.0043	AS
B24 (S)	LW	G	0	3.37×10^6	.0047	AS
B25 (A)	LW	P	NA	3.37×10^6	.0045	AS
B26 (S)	LW	P	SR	242997	.0041	AS
B27 (S)	LW	P	LF	1.49×10^6	.0033	AS
B28 (S)	LW	G	6	3.37×10^6	.0032	AS
B29 (S)	MW	G	6	3.37×10^6	.0043	AS
B30 (S)	LW	G	2	3.37×10^6	.0041	AS
B31 (S)	MW	P	LF	3.37×10^6	.0045	AS
B32 (S)	LW	P	SR	1.52×10^6	.0037	AS
B33 (S)	LW	P	1	1.85×10^6	.0031	AS
B34 (S)	LW	G	2	1.29×10^6	.0043	AS

Test Legend:
BS = Backup Screening
SS = Scraper Screening
LL = Long Life
AS = Additional Candidate Screening

Performance Legend:
E = Excellent
G = Good
F = Fair
P = Poor
SW = Severe Wear
MW = Moderate Wear
LW = Light Wear
LF = Leakage Failure > 300 ml
SR = Scored rod, not fault of candidate
(S) = Cres end cap
(A) = Aluminum bronze end cap
NA = Not available

TABLE 9. RATING OF BACKUPS BY O-RING CONDITION

O-RING CONDITION	BACKUP	INSTALLATION CODE AND NOTE(S)
EXCELLENT - No O-ring Damage	B3	2R; 1SS[4]
	B8	5R[3]; 3SS[4]
	B9	6L
	B20	7L
	B22	5L[5]; 7SS[4]
	B23	4 AS
	B35	1LL; 6LL
GOOD - Some Abrasion or Very Little Nibbling of O-ring	B1	(2SS, 3SS, 4SS, 5SS, 7SS, 8SS)[2]; 2L[1] (4AS, 6AS)[2,5]; 4LL, 2SS[1,4]
	B2	1R
	B20	4SS[4]
	B24	3 AS
	B28	1 AS
	B29	8 AS
	B30	1 AS[2]
	B34	2 AS[5]
FAIR - Moderate Abrasion or Nibbling of O-ring	B1	(1SS, 6SS)[2,4]; 1L; 7AS[2,5]
	B4	3L
	B9	8SS[4]
	B16	8L
	B19	8R
	B35	5LL[1]
	B22	2LL
POOR - Severe Nibbling and Damage to O-ring	B1	(2AS, 2AS, 3AS, 3AS, 4AS, 5AS, 5AS, 6AS, 7AS, 7AS)[2]; 2AS
	B5	5SS[4]; 3R
	B6	4L
	B10	6R
	B15	7R
	B17	4R
	B18	5L
	B21	7R; 6SS[4]
	B25	5AS
	B26	6AS
	B27	7AS
	B31	8AS
	B32	6AS
	B33	7AS

TABLE 9. RATING OF BACKUPS BY O-RING CONDITION (CONTINUED)

NOTES:
1. Installed in AL-Bronze end cap.
2. Installed in lug end of cylinder during scraper tests.
3. Backup was severely worn.
4. Not tested with impulse pressure.
5. Was not installed for all of test.

INSTALLATION CODE IN PARENTHESIS:

-2L = -2 assy, lug end, backup tests.
-3R = -3 assy, rod end, backup tests.
-6SS = -6 assy, scraper tests, rod end unless noted.
-5AS = -5 assy, additional screening test, rod end unless noted.
-4LL = -4 assy, Long Life Test, rod end.

Candidate B1; MS28774-214 (Baseline)

ASSEMBLY: No. 1 lug end, per 17-4PH end cap; No. 2 lug end, Al-bronze end cap, No. 2 rod end on retest.

CHARACTERISTICS EVALUATED: Std thickness, clearance ID fit, unfilled TFE, scarf cut, rectangular shape.

MATERIAL: Unfilled TFE

CONFIGURATION: See Figure 1. t = .045/.052, w = .118/.120, ID = 1.015 /1.017

RESULTS: Tested in a 17-4 PH CRES end cap and also in an aluminum bronze end cap.

CRES END CAP: See Figure 30. The backup sample in the CRES end cap exhibited moderate to heavy wear. The rod exhibited very light wear. The O-ring was nibbled on the OD and ID. Diametral clearance was .0038. Leakage was 8 drops in 1000 cycles.

ALUMINUM-BRONZE END CAP: See Figure 31. The backup sample in the aluminum-bronze end cap exhibited moderate wear. The O-ring was not damaged. No leakage was observed in 1000 cycles. Diametrical clearance was .0036

Candidate B1 was retested in the aluminum-bronze end cap during the scraper screening tests. See Figure 32. Diametral clearance was .0044. The backup showed some evidence of wear. The O-ring showed some abrasion and evidence of twisting. Very light wear of rod occurred with both installations in aluminum-bronze.

Candidate B2; S32974 -214-18

ASSEMBLY: No. 1 rod end

CHARACTERISTICS EVALUATED: Thickness, interference ID fit, material, uncut, rectangular shape

MATERIAL: Code 18 (W. S. Shamban)

CONFIGURATION: See Figure 2. t = .060/.064, w = .122/.124, ID = .992/.996

RESULTS: See Figure 33. The backup exhibited moderate to minimum wear. The O-ring showed some wear/nibbling on the ID. Upon completion of tests, the seal had 5 drops leakage in 1000 cycles. Diametral clearance was .0039 inches. The rod exhibited light wear.

Candidate B3; S32975-214-18

ASSEMBLY: No. 2 rod end; No. 1 rod end on retest.

CHARACTERISTICS EVALUATED: Thickness, interference ID fit, material, uncut, trapezoid shape.

MATERIAL: Code 18 (W. S. Shamban)

CONFIGURATION: See Figure 3. t = .075/.080, W = .108/.113, ID = .992/.996

RESULTS: See Figure 34. The backup exhibited minimum wear. The O-ring was not damaged. The seal had zero leakage in 1000 cycles. Diametral clearance was .0033 inches.

This backup was retested for 3.30×10^6 cycles. See Figure 35. Results were identical to the first test. Diametral clearance on the retest was .0039 inches. Total measurable leakage was 2 drops for the entire test. The rod exhibited a very light wear pattern after each test.

Candidate B4; CEC 5065-214

ASSEMBLY: No. 3 lug end.

CHARACTERISTICS EVALUATED: Thickness, interference ID fit, material, uncut, rectangular shape.

MATERIAL: Revonoc 18158 (C. E. Conover)

CONFIGURATION: See Figure 4. t = .060/.064, w = .118/.120, ID = .994/.996

RESULTS: See Figure 36. Tested as a single stage backup. The backup exhibited some wear and extrusion. The O-ring exhibited damage on both the OD and ID. The installation had .0042 in. diametral clearance. Leakage was 3 drops in 1000 cycles. Very light acceptable wear of rod occurred.

Candidate B5; CEC 5062-214NC

ASSEMBLY: No. 3 rod end; No. 5 rod end on retest

CHARACTERISTICS EVALUATED: Double thickness, interference ID fit, material, uncut, square shape.

MATERIAL: Revonoc 18158 (C. E. Conover)

CONFIGURATION: See Figure 5. t = .122/.126, w = .118/.120, ID = .994/.996

RESULTS: See Figure 37. Wear of the backup was moderate. The rod chrome plate was severely worn. The O-ring exhibited nibbling around the ID plus delamination of the upstream side. Leakage was 12.4 cc in 1000 cycles. Diametral clearance was .0042.

This candidate was retested and completed 3.30×10^6 cycles. See Figure 38. Total leakage was 0.6 ml. Diametral clearance was .0046 inches. The O-ring exhibited nibbling. The backup exhibited very little wear. The rod had light acceptable wear.

Candidate B6; TF855-214 and CEC 5083-214 Two Stage Backup

ASSEMBLY: No. 4 lug end

CHARACTERISTICS EVALUATED: Two stage, interference ID fit, material, uncut.

MATERIAL: Outboard-Polyimide (Vespel SP-1); Inboard - Unfilled TFE.

CONFIGURATION: See Figure 6

Outboard: t = .063 w = .121 ID = .996

Inboard: t = .048/.052, w = .118/.120, ID = .994/.996

RESULTS: See Figure 39. The TF855-214(outer) backup had minimum wear. The virgin TFE (inner) backup had moderate to severe wear. The O-ring exhibited damage on both the OD and ID. The assembly had 4 drops leakage in a 1000 cycle leak test on conclusion of screening tests. Diametral clearance was .0032 inches. The rod exhibited a moderate wear pattern around the circumference.

Candidate B8; DB12-02-214

ASSEMBLY: No. 5 rod end; No. 3 rod end on retest.

CHARACTERISTICS EVALUATED: Interference ID fit, uncut, triangle shape

MATERIAL: Unfilled TFE

CONFIGURATION: See Figure 7. t = N.A., w = .095/.109, ID = .994/.997

RESULTS: See Figure 40. The backup exhibited severe wear and extrusion to the point of almost being consumed. The O-ring was not damaged. No leakage occurred in a 1000 cycle test upon conclusion of the screening tests. Diametral clearance was .0032.

This candidate was retested for 3.30 x 10^6 cycles. See Figure 41. The backup exhibited very little evidence of wear. The O-ring was not damaged. Diametral clearance was .0034. Total leakage was 2 drops.

Candidate B9; MS27595-214 (CEC 5060-214)

ASSEMBLY: No. 6 lug end; No. 8 rod end on retest

CHARACTERISTICS EVALUATED: Std thickness, clearance ID fit, uncut, rectangular shape.

MATERIAL: Unfilled TFE

CONFIGURATION: See Figure 8. t = .048/.052, w = .118/.120, ID = 1.001/1.005.

RESULTS: See Figure 42. Completed 2.59 x 10^6 endurance cycles and 64200 impulse cycles at conclusion of test. The backup had minimum wear. The O-ring was not damaged. The seal had no leakage in 1000 cycles. Diametral clearance was .0025. The ID of this backup was 1.005 on initial installation. The ID had adjusted to the .9977 OD of the rod when removed upon conclusion of testing.

This candidate was retested for 3.30 x 10^6 cycles. See Figure 43. Diametral clearance was .0049. The O-ring exhibited slight nibbling and some wear. The backup ID had reduced to conform to the rod OD of .9964 inches.

Candidate B10; TF881-214

ASSEMBLY: No. 6 rod end.

CHARACTERISTICS EVALUATED: Interference ID fit, material, uncut, concave shape

MATERIAL: Tetralon 720

CONFIGURATION: See Figure 9. t = .089, W = .121, ID = .994

RESULTS: See Figure 44. The backup had minimum to moderate wear. The O-ring had uniform nibbling around the ID. 4 drops of leakage occurred during 1000 cycles. Diametral clearance was .0027.

Candidate B15; TF855-214

ASSEMBLY: No. 7 rod end.

CHARACTERISTICS EVALUATED: Thickness, interference ID fit, material, uncut, rectangular shape.

MATERIAL: Polyimide (Vespel SP-1)

CONFIGURATION: See Figure 10. t = .063, w = .121, ID = .996

RESULTS: See Figure 45. Removed after 226077 endurance cycles and 5604 impulse cycles when end cap scored piston rod at two localized points. Backup had minimum wear. O-ring had severe nibbling at two points corresponding to rod scoring plus uniform nibbling around ID. Diametral clearance was .0030.

Candidate B16; CEC 5083-214

ASSEMBLY: No. 8 lug end

CHARACTERISTICS EVALUATED: Std thickness, interference ID fit, uncut, rectangular shape.

MATERIAL: Unfilled TFE

CONFIGURATION: See Figure 11. t = .048/.052, w = .118/.120, ID= .994/.996

RESULTS: See Figure 46. The backup had moderate to heavy wear and extrusion. The O-ring was nibbled on the ID and showed evidence of being twisted. No leakage was reported in 1000 cycles. Diametral clearance was .0024.

Candidate B17; CEC 5075-214NC

ASSEMBLY: No. 4 rod end.

CHARACTERISTICS EVALUATED: Thickness, interference ID fit, uncut, square shape.

MATERIAL: Unfilled TFE

CONFIGURATION: See Figure 12. t = .122/.126, w = .118/.120, ID = .994/.996

RESULTS: See Figure 47. Wear of the backup was moderate. The O-ring exhibited nibbling on the ID and OD. Leakage was 11 drops in 1000 cycles. Diametral clearance was .0030.

Candidate B18; CEC 5083-214

ASSEMBLY: No. 5 lug end.

CHARACTERISTICS EVALUATED: Two stage, interference ID fit, uncut.

MATERIAL: Unfilled TFE inboard and outboard.

CONFIGURATION: See Figure 13

Inboard: t = .048/.052, w = .118/.120, ID = .994/.996
Outboard t = .048/.052, w = .118/.120, ID = .994/.996

RESULTS: See Figure 48. Tested as a two stage backup with both backup rings on one side of O-ring. Catastrophic failure at 1.43 x 10^6 endurance cycles. Backups exhibited severe wear on one side. The O-ring extruded and blew out on the OD at one spot. Diametral clearance was .0035.

Candidate B19; TF830-214-1 and TF830-214-2 Two Stage Backup

ASSEMBLY: No. 8 rod end.

CHARACTERISTICS EVALUATED: Two stage, interference ID fit, material, uncut.

MATERIAL:

Inboard - Tetralon 720
Outboard - Polyimide (Vespel SP-1)

CONFIGURATION: See Figure 14.

Inboard	= t = .063	w = .120	ID = .995
Outboard	= t = .047	w = .112*	ID = .995

* Reduced OD on outboard backup to allow radial displacement of backup with rod.

RESULTS: See Figure 49. The TF830-214-1 (outer) backup had minimum wear. The TF830-214-2 (inner) backup flowed around the OD of the outer backup and was pulling away on the ID. The O-ring was nibbled on the ID. The assembly had zero leakage in 1000 cycles. Diametral clearance was .0033.

Candidate B20; TF1007-214-2 and TF1007-214-3 Two Stage Backup

ASSEMBLY: No. 7 lug end; No. 4 rod end on retest.

CHARACTERISTICS EVALUATED: Two stage, clearance ID fit, material, spiral construction.

MATERIAL:

Inboard - Tetralon 700

Outboard - Glass/M_oS_2 filled TFE

CONFIGURATION: See Figure 15.

Inboard and Outboard t = .025/.029, w = .119/.121,
ID = 1.000/.998

RESULTS: See Figure 50. Both backups exhibited minimum wear. The O-ring was not damaged. The assembly had 3 drops leakage in 1000 cycles. Diametral clearance was .0028.

This candidate was retested for 3.30 x 10^6 cycles. See Figure 51. The O-ring had some abrasion on the ID. The backups exhibited minimum wear. Total leakage was 3 ml. Diametral clearance was .0031.

Candidate B21; S33012-214-14

ASSEMBLY: No. 7 rod end; No. 6 rod end on retest.

CHARACTERISTICS EVALUATED: Heavy duty thickness, interference ID fit, filled material, uncut, rectangular shape.

MATERIAL: Glass/MoS_2 filled TFE, W. S. Shamban Code 14.

CONFIGURATION: See Figure 16. t = .060/.064, w = .118/.120, ID = .992/.996.

RESULTS: See Figure 52. Completed 2.76×10^6 endurance cycles and 68415 impulse cycles at conclusion of test. The backup ID had worn to approximately .998 inches. The O-ring had nibbling on the ID and had twisted in the groove. Leakage was 15 drops in 1000 cycles. Light rod wear was evident. Diametral clearance was .0032.

This candidate was retested for 3.3×10^6 cycles. See Figure 53. Diametral clearance was .0043. Backup, O-ring, and rod condition were the same as in the previous test. Leakage was 92.5 ml for the entire test. The backup ID had worn to .998 inches.

Candidate B22; CEC 4862-214NC

ASSEMBLY: No. 5 lug end; No. 7 rod end on retest.

CHARACTERISTICS EVALUATED: Two stage, interference ID fit, material uncut.

MATERIAL: Inboard and Outboard - 18158 (C. E. Conover).

CONFIGURATION: See Figure 17. Inboard and Outboard: t = .060/.064, w = .118/.170, ID= .994/.996

RESULTS: See Figure 54. Tested as a two stage backup with both backups on one side of O-ring. Completed 1.63×10^6 endurance cycles and 40400 impulse cycles at conclusion of tests. The backups exhibited minimum wear. The O-ring exhibited no damage. No leakage was observed in a 1000 cycle leakage test. Diametral clearance was .0035.

This candidate was retested for 3.30×10^6 cycles. See Figure 55. The O-ring was undamaged. Minimum backup wear occurred. Total leakage was 1 drop. Diametral clearance was .0030.

The following additional candidates were evaluated after completion of the Long Life Tests. Unless noted, test conditions were as follows: Inlet oil temperature 265 - 275°F, box ambient temperature 170 - 190°F. Constant 3000 psig was applied during endurance cycling. 3.375×10^6 endurance cycles were accomplished in blocks which had proportions of cycles in accordance with the FBW endurance spectrum. A total of 111014 impluse cycles of 0 - 4500 psig were applied by application of 5000 cycles after each days dynamic cycling.

Candidate B1; MS28774-21 (Baseline)

ASSEMBLY: No. 2 Rod End

CHARACTERISTICS EVALUATED: Standard thickness, clearance ID fit, unfilled TFE, scarf cut, rectangular shape.

MATERIAL: Unfilled TFE

CONFIGURATION: See Figure 1. t = .045/.052, w = .118/.120, ID = 1.015/1.017.

RESULTS: See Figure 56. Failed catastrophically after 2,083,452 endurance plus 86014 impulse cycles. The O-ring was uniformally nibbled on the ID except for a .20 inch wide area where approximately one-half of the O-ring cross section was missing. This severely damaged area corresponded to a locally worn area on the ID of the backup which appears to have extruded sufficiently to allow the O-ring to blow out. The piston rod had very light wear. The backup had adequate overlap. Wear of the backup cross section was .6 percent. Diametral clearance was .0043. Static leakage was 2 drops. Dynamic leakage exceeded 300 ml (failure).

Candidate B1; MS28774-214 Rod Seals used with Scraper Screening Tests

ASSEMBLY: Assemblies 1 thru 8, lug end.

CHARACTERISTICS EVALUATED: Standard thickness, clearance ID fit, unfilled TFE, scarf cut, rectangular shape.

MATERIAL: Unfilled TFE.

CONFIGURATION: See Figure 1.

RESULTS: See Figure 57. The rod seal used exclusively with the scrapers during screening tests of scrapers has been an M83461/1-214 O-ring with MS28774-214 backups. These seals were not considered to be part of the backup ring candidates due to the fact they operated on the contaminated rod end with the crew tester assembly. The performance of these backups should be considered to some extent due to the quantities involved. Eight MS28774 backup installations were used in the first set of scraper screening tests. Fourteen installations were made for the screening tests on additional scraper candidates. The average diametral clearance of the bore to rod on the first tests was .0039, but the seals were not impulse tested. No rod seal failures occurred. The tests on additional scraper candidates included 0-4500 impulse testing to aid in evaluation of the backup candidates. Eight rod seal failures with MS28774 backups occurred. Average diametral clearance was .0041. Failures

occurred at 1.52 million, 2.08 million, 2.27 million, and 2.70 million cycles. When the chew testers were disassembled, O-rings and backups with 925700 cycles had begun to nibble and roll and failure was imminent on another with 1.29 million cycles. Figure 32 shows the typical appearance of MS28774-214 backups removed after 3.3×10^6 endurance cycles and no impulse pressure testing. Temperature was between 170 and 220°F during test. Figure 58 shows the typical appearance of MS28774-214 backups removed after as little as 1.52 million endurance cycles and 66000 impulse cycles.

Candidate B23; S32975-214-20

ASSEMBLY: No. 4 Rod End.

CHARACTERISTICS EVALUATED: Thickness, interference ID fit, material, uncut, trapezoid shape.

MATERIAL: Code 20 (W. S. Shamban)

CONFIGURATION: See Figure 18. (Same as B3)

RESULTS: See Figure 59. The O-ring was undamaged. Rod wear was very light with what appeared to be a polishing off of high spots in the grind marks in the chrome. Backup wear was moderate with 4.3 percent wear of cross section. The ID had increased to .998 from .994 initially. Diametral clearance was .0040. Dynamic leakage was 10 drops. Static leakage was 0.

Candidate B24; CEC 5110-214

ASSEMBLY: No. 3 Rod End.

CHARACTERISTICS EVALUATED: Thickness, interference ID fit, material, uncut, rectangular shape.

MATERIAL: Revonoc 6200 (C. E. Conover)

CONFIGURATION: See Figure 19. (Same as B4)

RESULTS: See Figure 60. The O-ring had very light nibbling on the ID and is classified as good condition. The backup ID had increased to .998 from .994 when new. Cross section wear was low with 1 percent reduction. Rod wear was very light. The appearance is that of polishing off the high spots in the grind marks in the chrome plate. Diametral clearance was .0047. Dynamic leakage was 0. Static leakage was 0.

Candidate B25; TF-XXX-2-2

ASSEMBLY: No. 5 Rod End.

CHARACTERISTICS EVALUATED: Thickness, interference ID fit, material, uncut, rectangular shape.

MATERIAL: Polyimide (Vespel SP-21).

CONFIGURATION: See Figure 20. t = .060/.065; w = .118/.121; ID = .988/.992.

RESULTS: See Figure 61. The O-ring was severely nibbled on the ID and had rolled. The backup was in good condition with low (2.2 percent) wear. The polyimide is abrasive. The rod is moderately worn with uniform axial wear marks around the rod circumference in the area of the rod contacted by the seal during the 1, 2, and 10 percent stroke cycling. The diametral clearance was .0045. Static leakage = 0. Dynamic leakage = 0. Static and dynamic leakage for this candidate are shown as zero, however this is erroneous due to the fact that the wiper O-ring, which should have caused all leakage to be collected in the container provided, was broken into pieces. Failure of the wiper O-ring was due to spiral failure and air ageing.

Candidate B26; TF-XXX-2-3

ASSEMBLY: No. 6 Rod End.

CHARACTERISTICS EVALUATED: Thickness, interference ID fit, material, uncut, rectangular shape.

MATERIAL: Delrin Acetal Resin.

CONFIGURATION: See Figure 21. t = .060/.065; w = .119/.122; ID = .986/.990.

RESULTS: See Figure 62. Removed after 242997 endurance and 10000 impulse cycles when the rod scored allowing the O-ring to blow out between the backup and the groove in the rod. The rod was scored along a .03 x 2.0 dimension. The backups were undamaged except for an indention on the outboard side of the outboard backup. The indention was caused by displaced metal in the end cap bore projecting into the groove. The O-ring had a single large notch on the ID corresponding to the scored area on the rod. The O-ring also had moderate nibbling around the ID and around one-half of the OD. Diametral clearance was .0041. Because of the O-ring damage in such a short time, no additional testing was done on this candidate. Low wear (1.3 percent). ID had increased to .9903 from .986.

Candidate B27; TF-XXX-1-2

ASSEMBLY: No. 2 Rod End

CHARACTERISTICS EVALUATED: Thickness, interference ID fit, material, uncut, trapezoid shape.

MATERIAL: Polyimide (Vespel SP-21).

CONFIGURATION: See Figure 22. t = .13; w = .118/.121; ID = .988/.992.

RESULTS: See Figure 63. Removed after 1,525,121 endurance cycles and 66000 impulse cycles due to excessive dynamic leakage which first began at Block 9 and increased until removal after Block 13. The O-ring was severely nibbled and damaged on the entire ID. The backup had low wear (1.3 percent). The backup ID had increased to approximately .994 versus .9903 new. The rod had light wear. Diametral clearance was .0033. Static leakage was 1 drop. Dynamic leakage exceeded 300 ml; bottle ran over.

Candidate B28; TF-XXX-1-1

ASSEMBLY: No. 1 Rod End.

CHARACTERISTICS EVALUATED: Thickness, interference ID fit, material, uncut, trapezoid shape.

MATERIAL: Delrin Acetal Resin.

CONFIGURATION: See Figure 23. t = .13; w = .118/.121; ID = .986/.990.

RESULTS: See Figure 64. O-ring has very light nibbling on OD and ID and is classified as good condition. The backup still had an interference fit with rod at good temperature. The backup had low wear (1.8 percent on cross section). Rod wear was light with several small areas polished deeper than the original 8 RMS finish. Diametral clearance = .0032. Static leakage was 0. Dynamic leakage was 6 drops.

Candidate B29; CEC 5056-214

ASSEMBLY: No. 8 Rod End

CHARACTERISTICS EVALUATED: Thickness, interference ID fit, material, uncut, trapezoid shape.

MATERIAL: Revonoc 6200 (C. E. Conover).

CONFIGURATION: See Figure 24. t = .13; w = .13, ID = .990

RESULTS: See Figure 65. B29 trapezoid backup in Revonoc 6200 backup has moderat[illegible] [illegible]r (5.2 percent). O-ring has light extrusion on OD with localized nibb[illegible] on ID. O-ring is classified as good. Diametral clearance was .0[illegible]3. Rod had very light wear. No static leakage. Dynamic leakage was 6 drops.

Candidate B30; S32975-214-99

ASSEMBLY: No. 1 Lug End.

CHARACTERISTICS EVALUATED: Thickness, interference ID fit, material, uncut, trapezoid shape.

MATERIAL: MoS_2 filled T[illegible] [illegible] W. S[illegible] [illegible]hamban Compound 99).

CONFIGURATION: See Figure 25. (Same as B3)

RESULTS: See Figure 66. O-ring is in excellent condition with no damage. O-ring ID has increased to approximately .998 as is typical with this type of backup. The backup has very little wear with .86 percent reduction in cross section. The ID is approximately .997 corresponding to the rod diameter of .9978. Diametral clearance was .0041. The piston rod was discolored by the MoS_2 in the backup. Rod wear is moderate with axial wear wear marks around the circumference at least as deep as the original 7 RMS finish. Static leakage was 0. Dynamic leakage was 2 drops.

Candidate B31; TFE-XXX-2-1

ASSEMBLY: No. 8 Rod End

CHARACTERISTICS EVALUATED: Thickness, interference ID fit, material, uncut, rectangular shape.

MATERIAL: Acetal Resin with TFE filler (Tetrafluor, Inc.)

CONFIGURATION: See Figure 26. t = .060/.065; w = .118/.121; ID = .986/.990

RESULTS: See Figure 67. Backup has moderate wear (8.9 percent). O-ring has rolled and is nibbled over a large area of what was the ID. O-ring is classified as poor. Diametral clearance was .0045. Rod finish is dulled and characterized by axial wear marks which are at least as deep as the original 9 RMS finish. Rod wear is classified as high. Average static leakage was 53 ml/day (Blocks 13 thru 29). Dynamic leakage exceeded 300 ml leakage (failure).

Candidate B32; TF95A - 7214A

ASSEMBLY: No. 6 Rod End

CHARACTERISTICS EVALUATED: Thickness, interference ID fit, material, uncut, rectangular shape.

MATERIAL: Low carbon fill polymer (Tetrafluor, Inc.)

CONFIGURATION: See Figure 27. t = .060/.065; w = .118/.121; ID = .986/.990.

RESULTS: See Figure 68. Testing continued until 1,275,124 endurance cycles plus 56000 impulse cycles were applied when the piston rod scored. The piston rod was replaced retaining the same O-ring and backups and testing resumed. Rod scoring occurred again after 236742 endurance cycles plus 10014 impulse cycles were applied. After each failure the bore of the end cap was inspected and polished and all known measures to assure a good assembly were exercised. Assembly No. 6 was shut down after the last rod scoring incident having exhausted current available remedies for prevention of scoring and having no additional piston rods for installation. Subsequent to the test program, it was determined that the purchased parts of the chew tester assembly were out of tolerance on parallelism requirements which could result in side loading of the end cap by the rod. Backup wear was low (2.1 percent).

Candidate B33; TF95-7214-600

ASSEMBLY: No. 7 Rod End

CHARACTERISTICS EVALUATED: Thickness, interference ID fit, uncut, material, rectangular shape.

MATERIAL: Carbon filled TFE (Tetrafluor, Inc.)

CONFIGURATION: See Figure 28. t = .052; w = .121; ID = .998

RESULTS: See Figure 69. Completed 1,850,343 endurance plus 45014 impulse cycles. O-ring is severely nibbled on the ID. O-ring has rolled. O-ring condition is poor. The outboard backup ID has increased to ≈ .990 from .998. Cross section wear is low (2.1 percent). Diametral clearance was .0031. The rod was darkened by the carbon filler and is moderately worn. Static leakage was 1 drop. Dynamic leakage was 1 drop.

Candidate B34; TF95A-7214B

ASSEMBLY: No. 2 Rod End

CHARACTERISTICS EVALUATED: Thickness, interference ID fit, uncut, material, rectangular shape.

MATERIAL: High fill carbon polymer (Tetrafluor, Inc.)

CONFIGURATION: See Figure 29. t = .060/.065; w = .118/.121; ID = .986/.990.

RESULTS: See Figure 70. The O-ring has some nibbling around the ID and is classified as good condition after exposure to 1,292,012 endurance plus 25000 impulse cycles. The outer backup was not worn. The piston rod wear was very light. Diametral clearance was .0043. Static leakage was 0. Dynamic leakage was 2 drops.

Candidate B35; S32975-214-19; W. S. Shamban

See Section 4, Long Life Test Results.

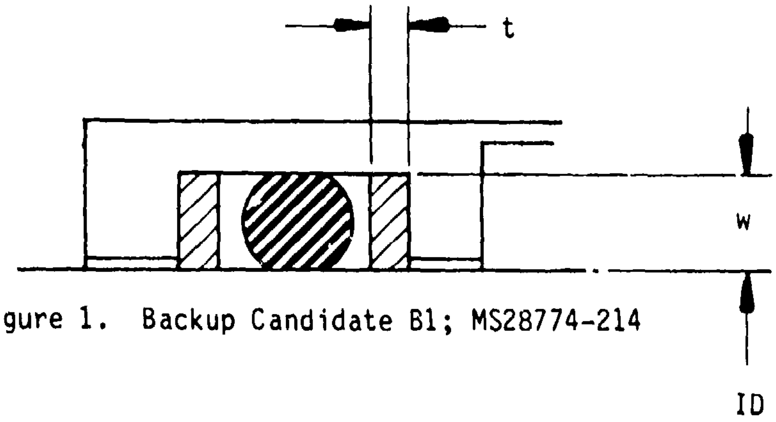


Figure 1. Backup Candidate B1; MS28774-214

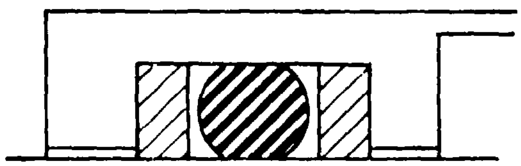


Figure 2. Backup Candidate B2; S32974-214-18

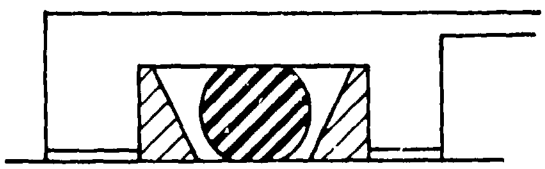


Fig: re 3. Backup Candidate B3; S32975-214-18

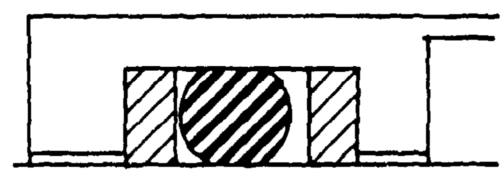


Figure 4. Backup Candidate B4; CEC 5065-214

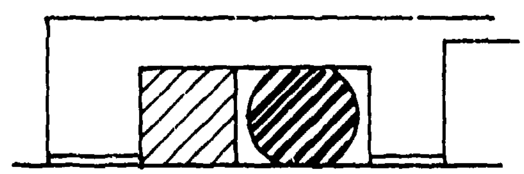


Figure 5. Backup Candidate B5; CEC 5062-214NC

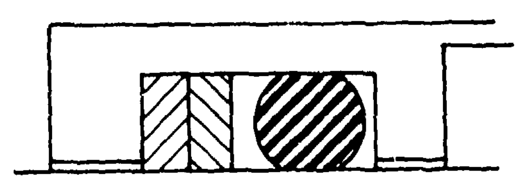


Figure 6. Backup Candidate B6; TF855-214 and Unfilled TFE Two Stage Backup

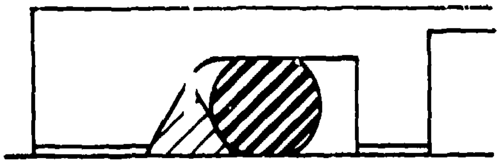


Figure 7. Backup Candidate B8; DB12-02-214

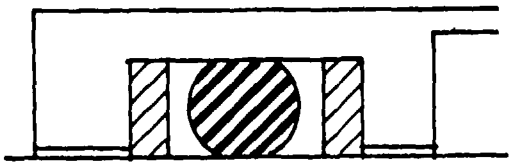


Figure 8. Backup Candidate B9; MS27595-214

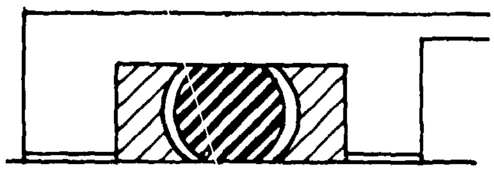


Figure 9. Backup Candidate B10; TF881-214

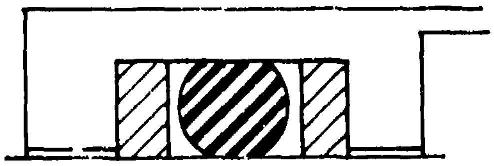


Figure 10. Backup Candidate B15; TF855-214

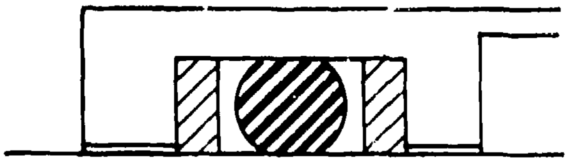


Figure 11. Backup Candidate B16, CEC 5083-214

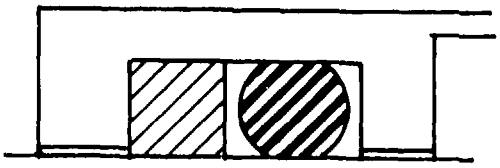


Figure 12. Backup Candidate B17; CEC 5075-214NC

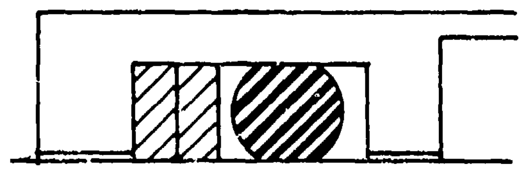


Figure 13. Backup Candidate B18; CEC 5083-214

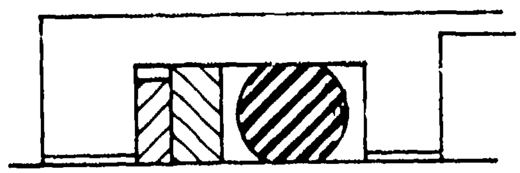


Figure 14. Backup Candidate B19; TF830-214-1 and TF830-214-2 Two Stage Backup

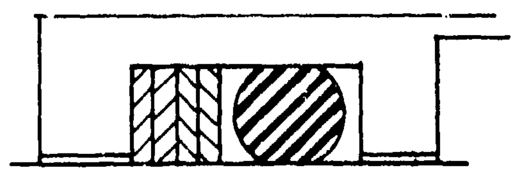


Figure 15. Backup Candidate B20; TF1007-214-2 and TF1007-214-3 Two Stage Backup

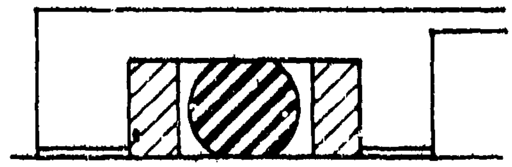


Figure 16. Backup Candidate B21; S33012-214-14

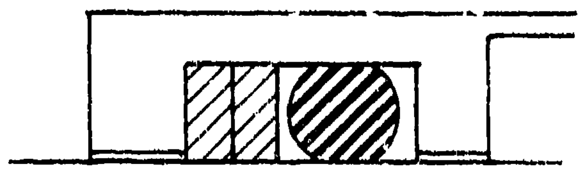


Figure 17. Backup Candidate B22; CEC 4862-214NC

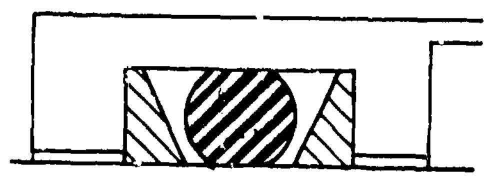


Figure 18. Backup Candidate B23; S32975-214-20

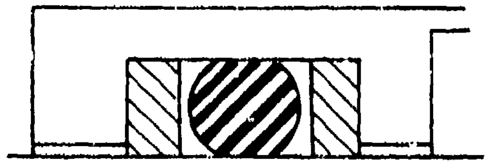


Figure 19. Backup Candidate B24; CEC 5110-214

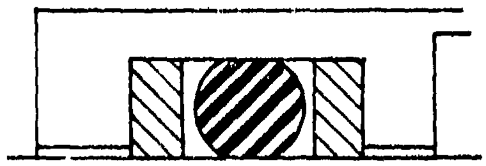


Figure 20. Backup Candidate B25; TF-XXX-2-2

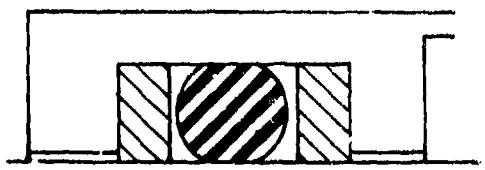


Figure 21. Backup Candidate B26; TF-XXX-2-3

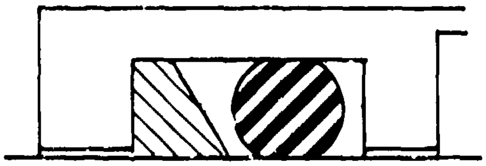


Figure 22. Backup Candidate B27; TF-XXX-1-2

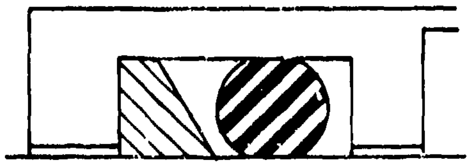


Figure 23. Backup Candidate B28; TF-XXX-1-1

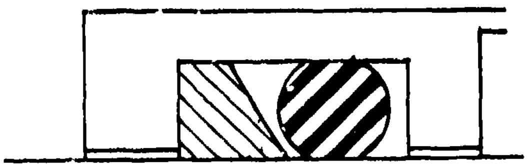


Figure 24. Backup Candidate B29; CEC 5056-214

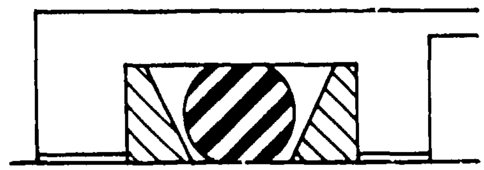


Figure 25. Backup Candidate B30; S32975-214-99

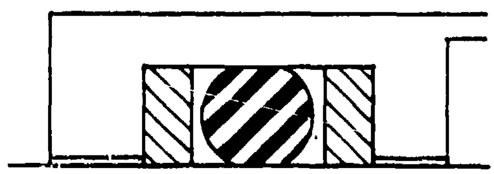


Figure 26. Backup Candidate B31; TF-XXX-2-1

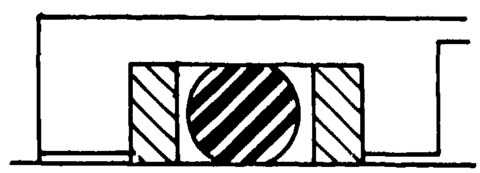


Figure 27. Backup Candidate B32; TF95A-7214A

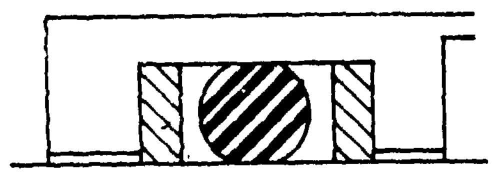


Figure 28. Backup Candidate B33; TF95-7214-600

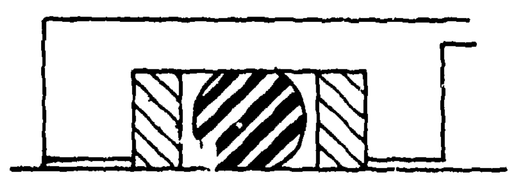


Figure 29. Backup Candidate B34; TF95A-7214B

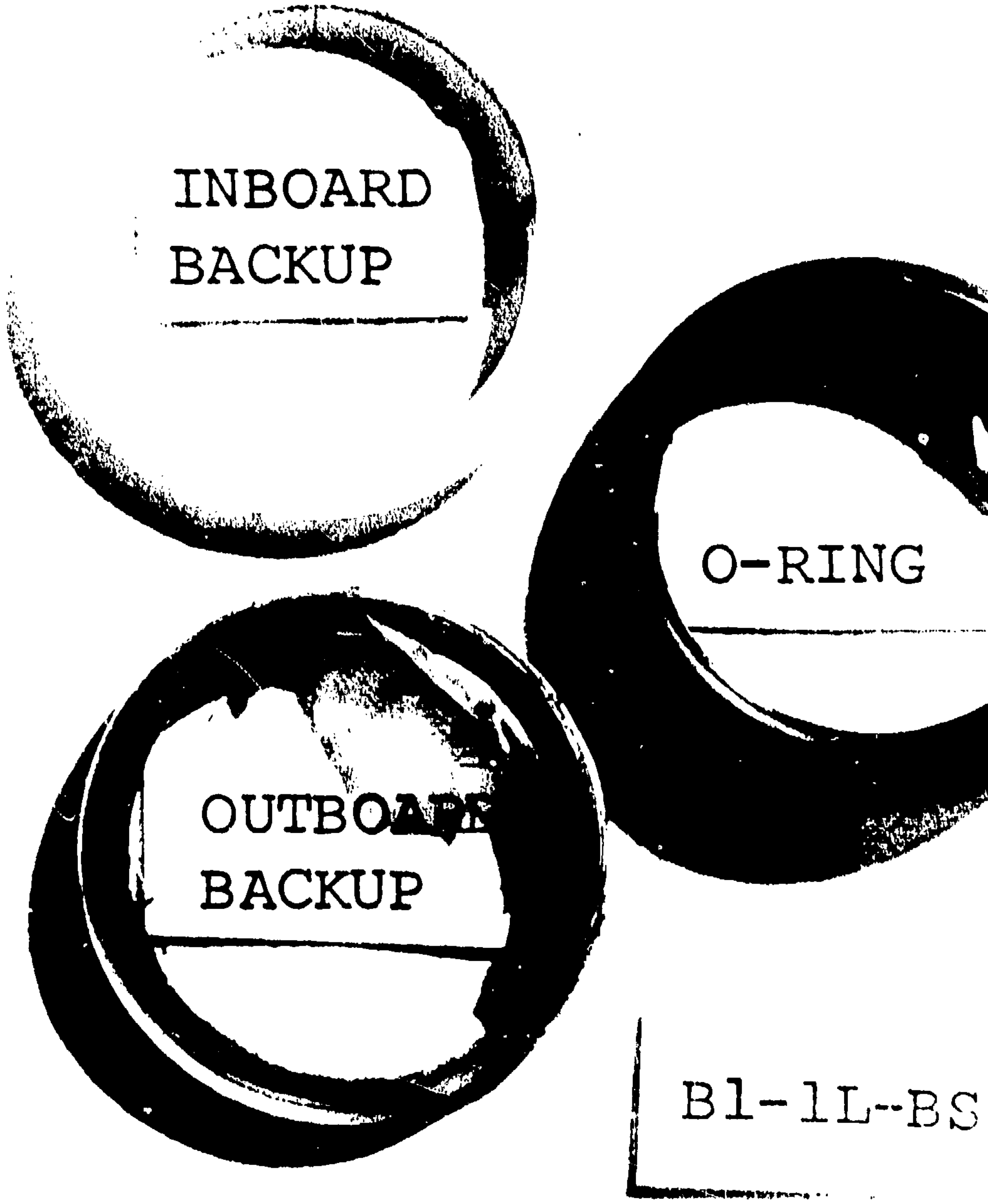


Figure 30. Candidate B1 After Backup Screening Test - Cres End Cap Installation. O-ring condition is fair.

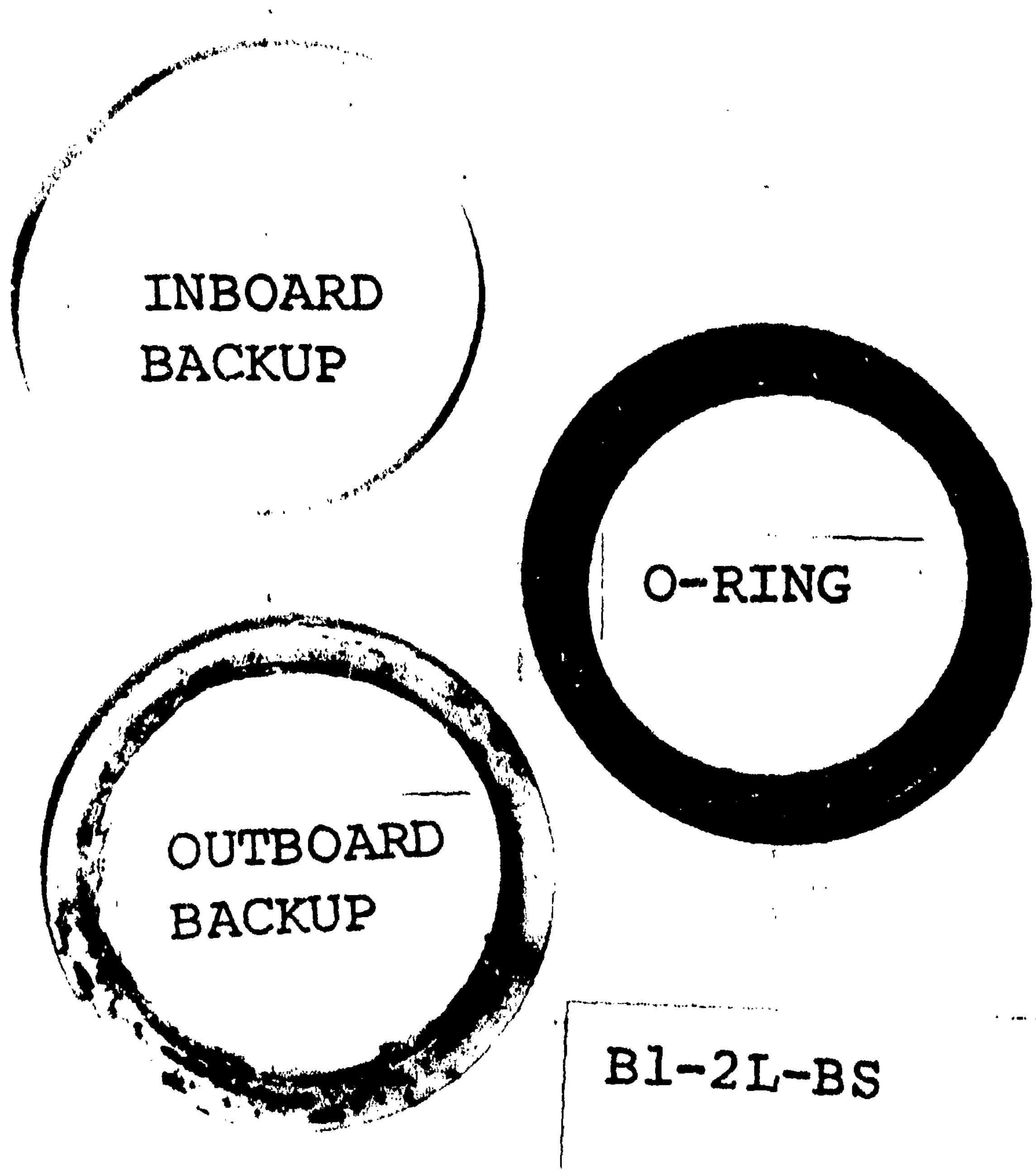


Figure 31. Candidate B1 After Backup Screening Test - Aluminum Bronze End Cap Installation. O-ring condition is good.

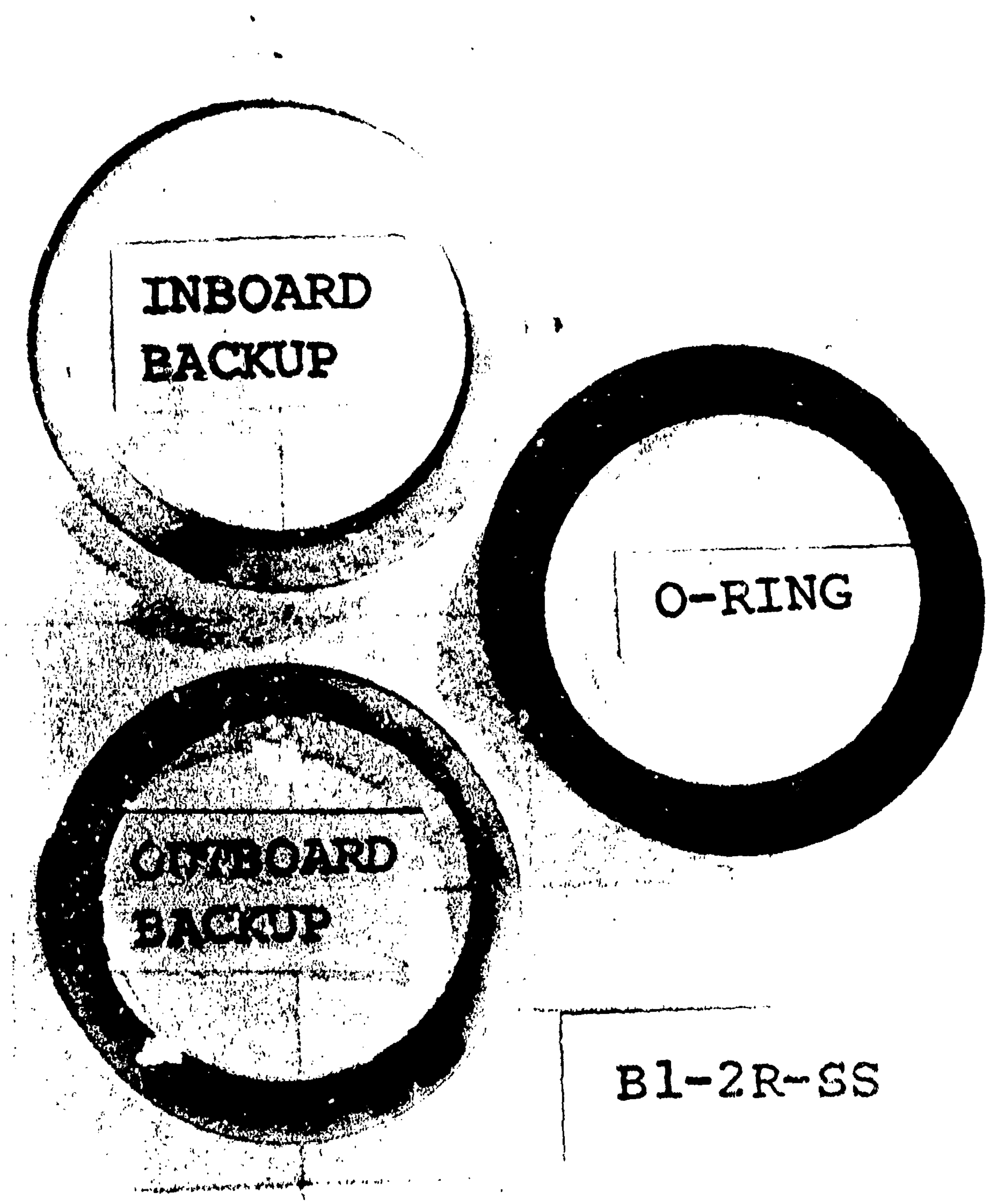


Figure 32. Candidate B1 After 3.30×10^6 Endurance Cycles With No Impulse Testing - Aluminum Bronze End Cap Installation. O-ring condition is good.

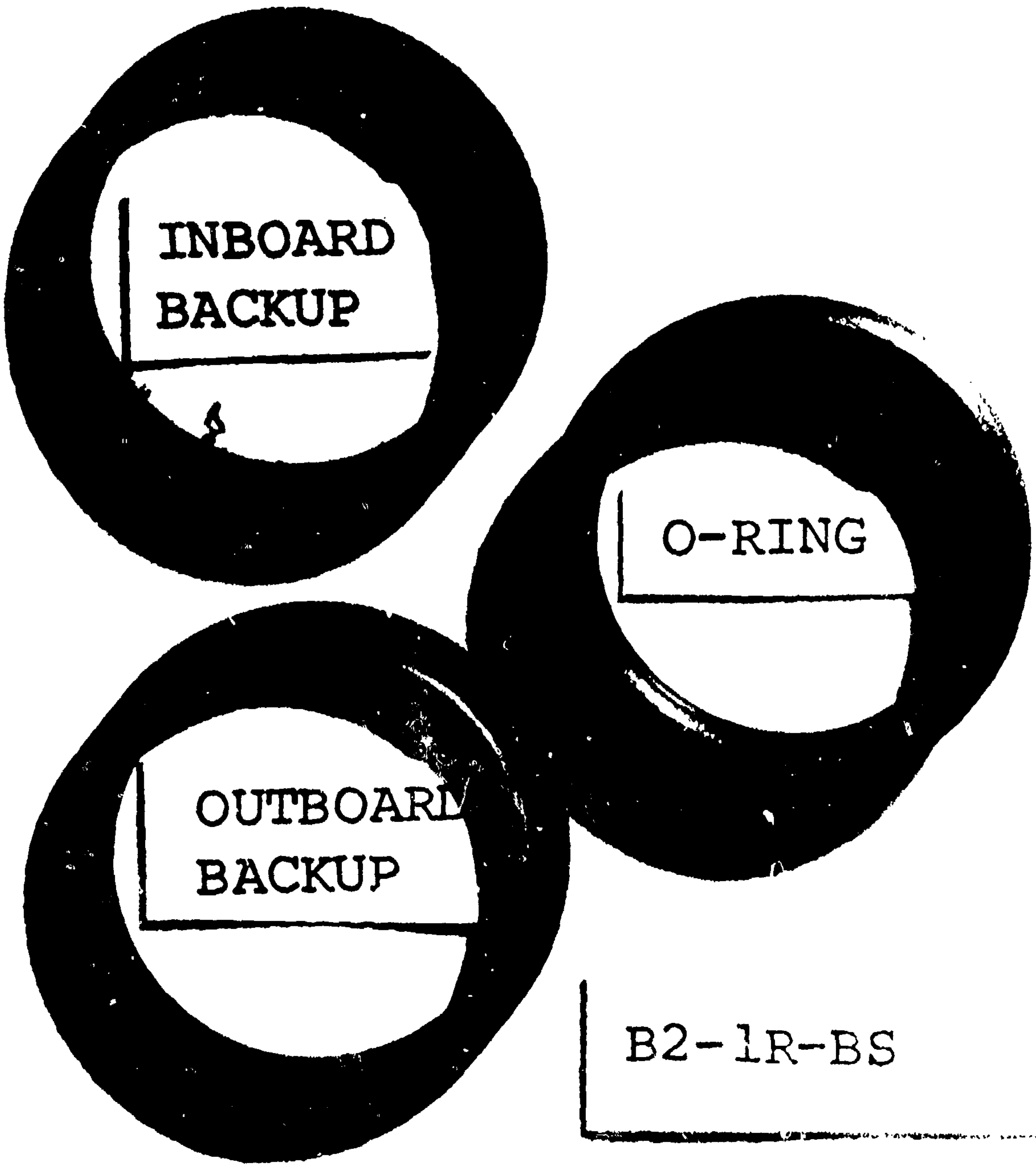


Figure 33. Candidate B2 After Backup Screening Test. O-ring condition is good.

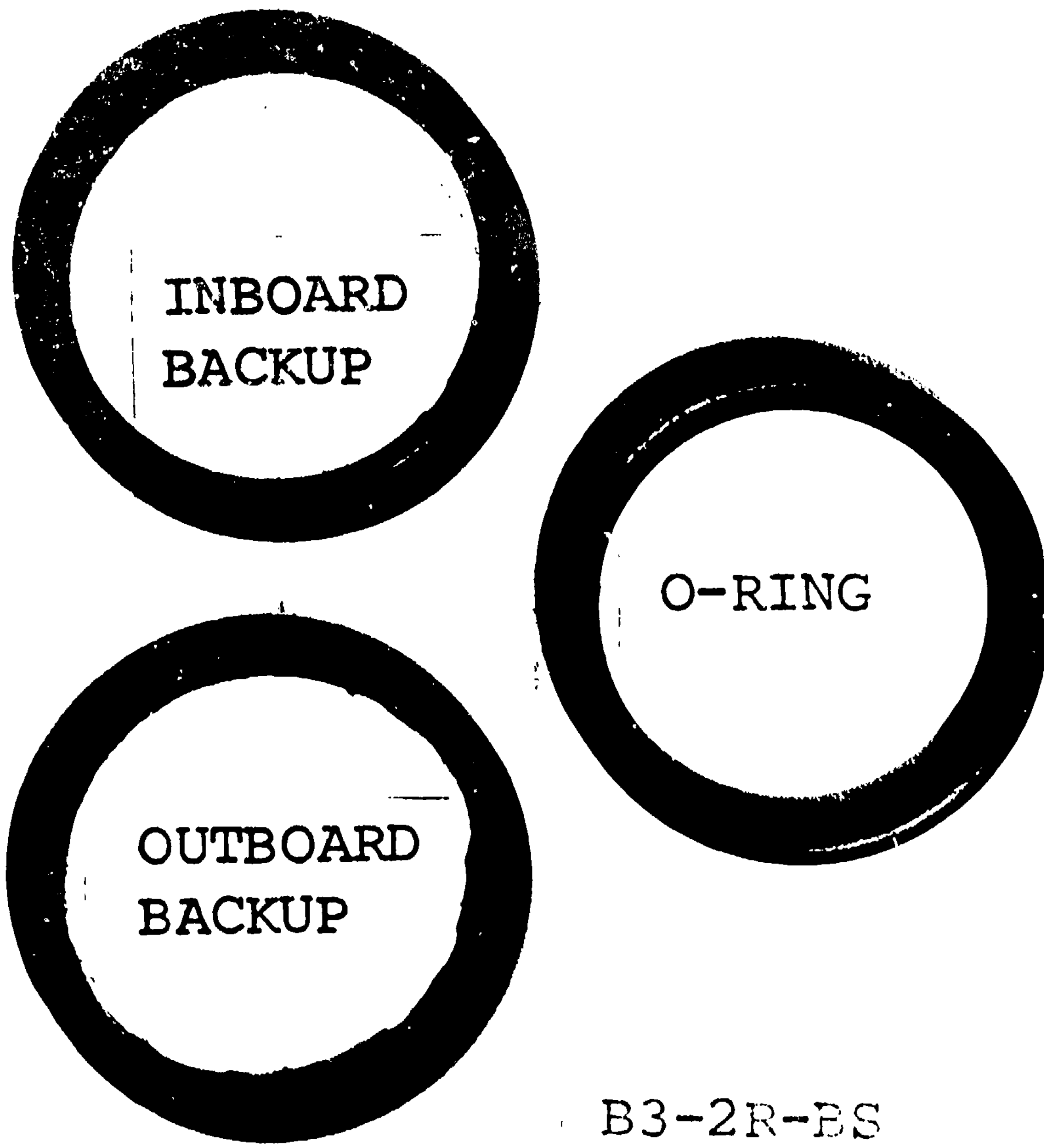


Figure 34. Candidate B3 After Backup Screening Test. O-ring condition is excellent.

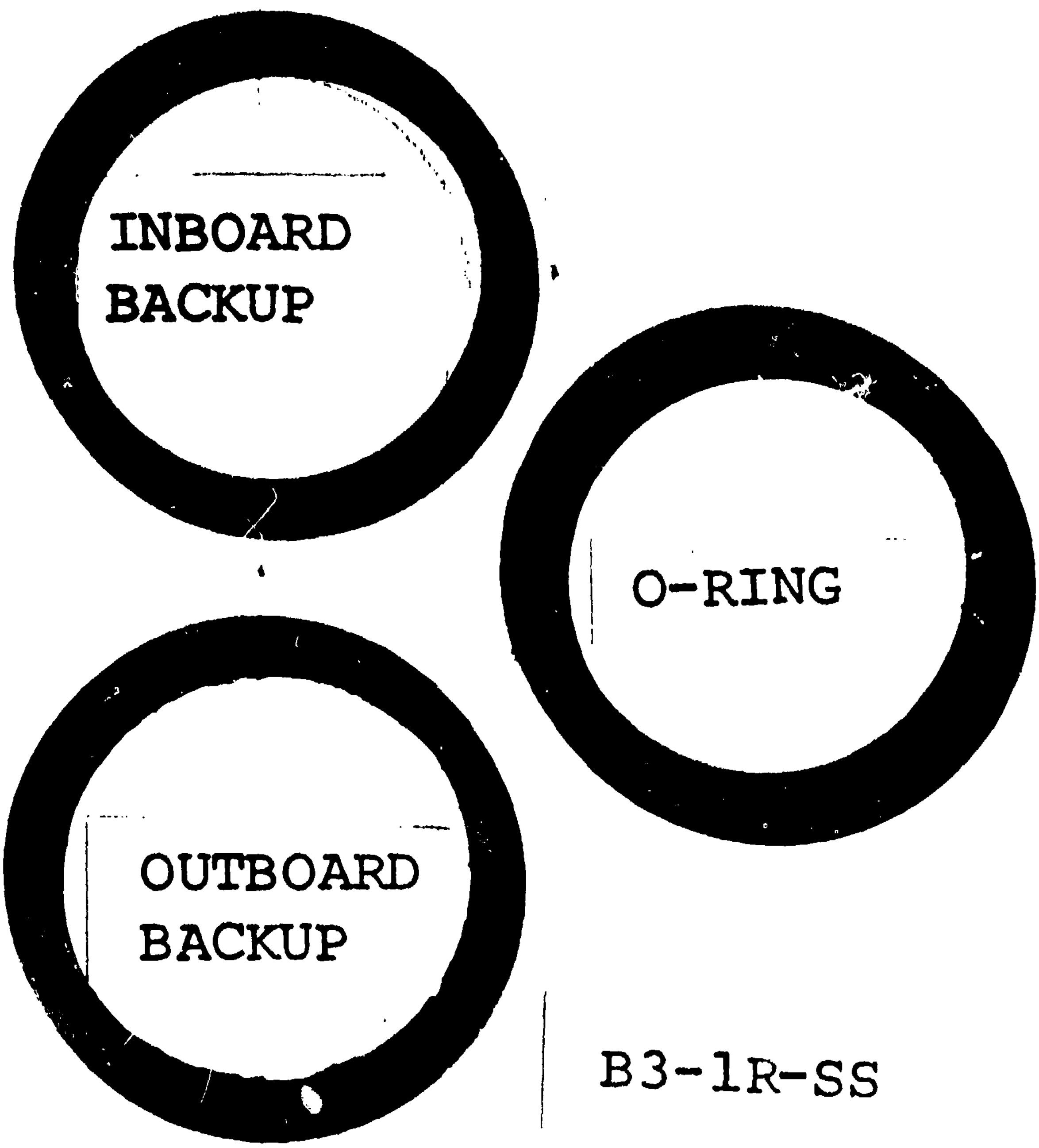


Figure 35. Candidate B3 After 3.30 x 10^6 Endurance Cycles with no Impulse Testing. O-ring condition is excellent.

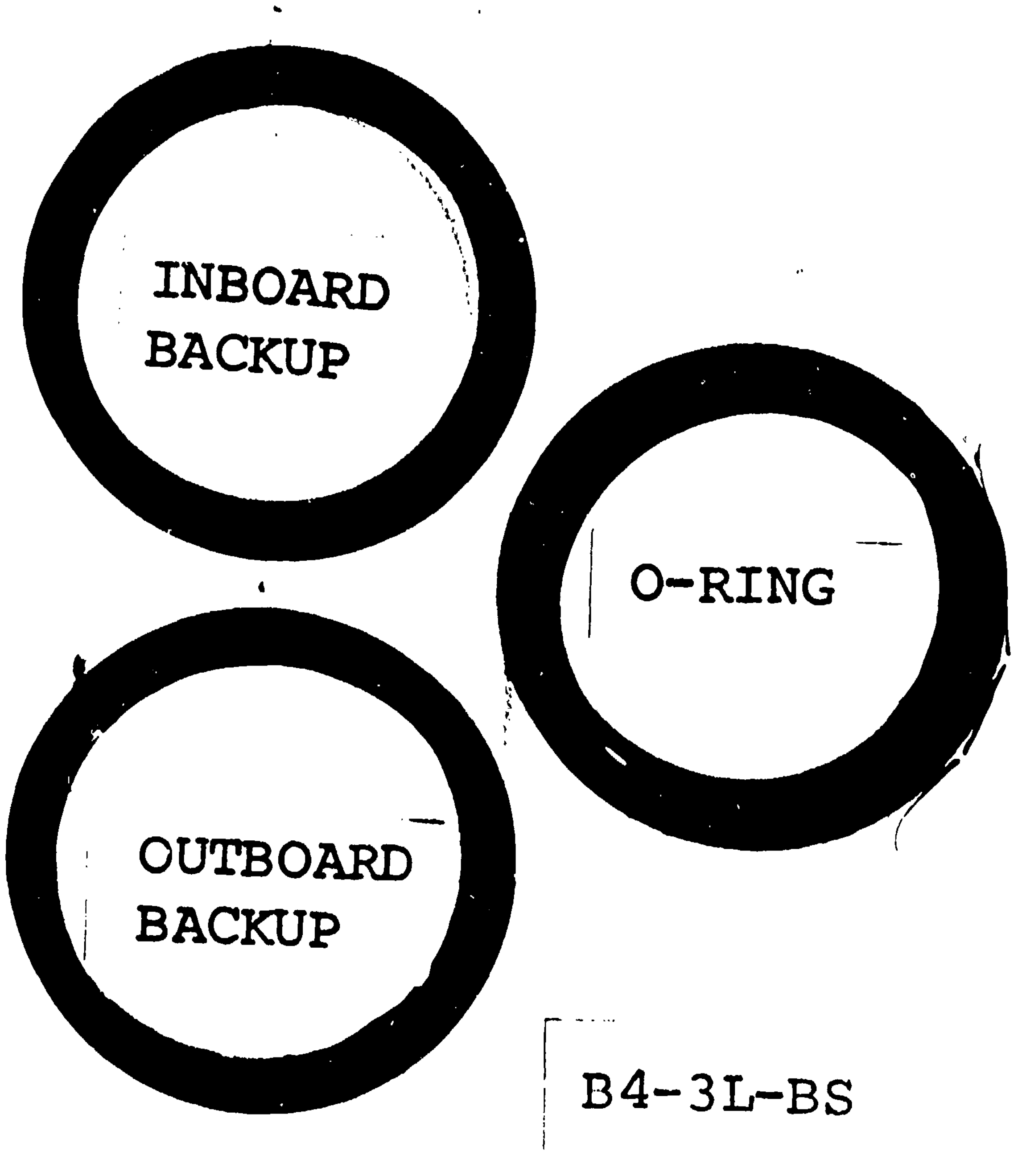


Figure 36. Candidate B4 After Backup Screening Test. O-ring is nibbled on the OD and ID.

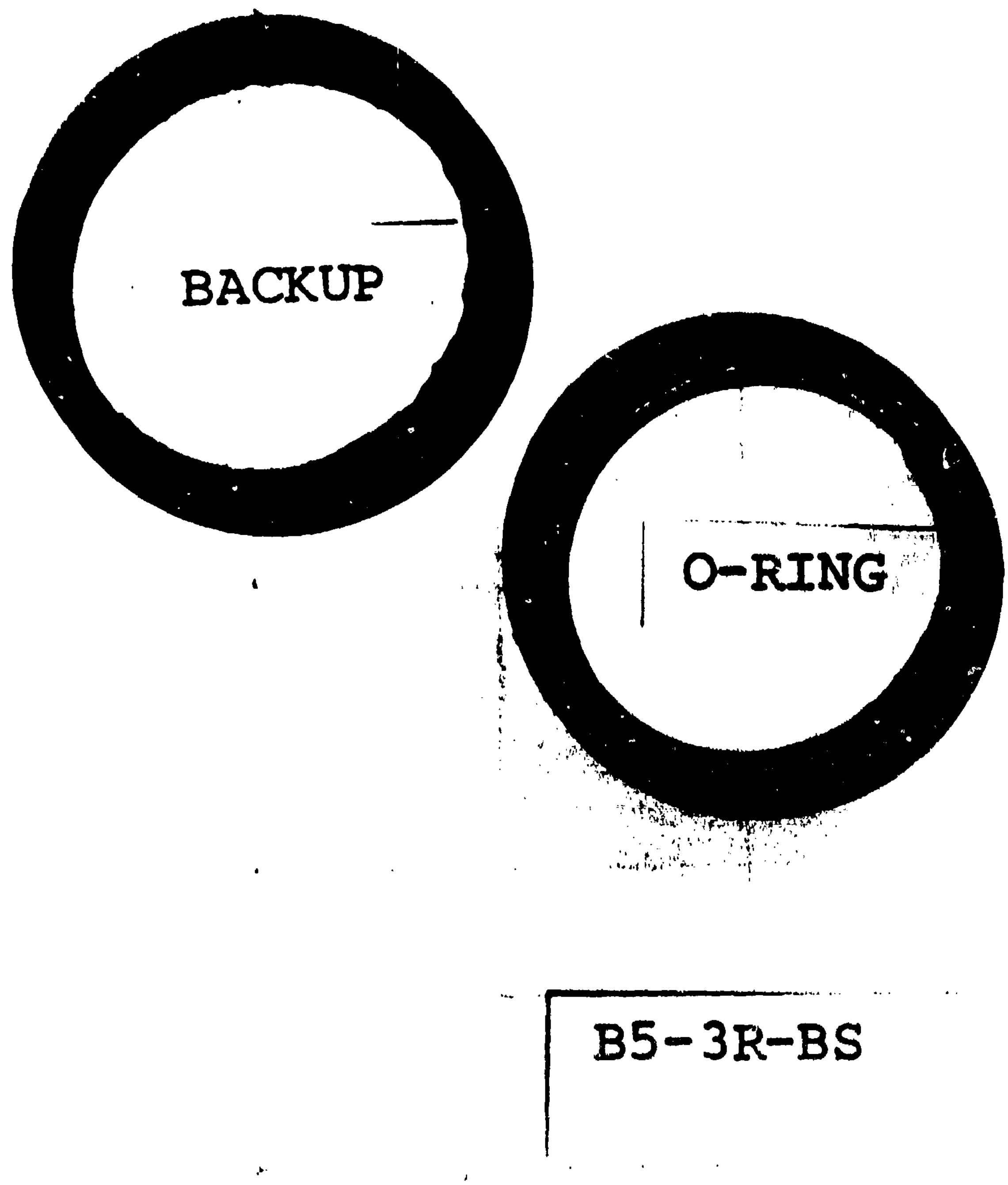


Figure 37. Candidate B5 After Backup Screening Test.
O-ring is nibbled, condition is poor.

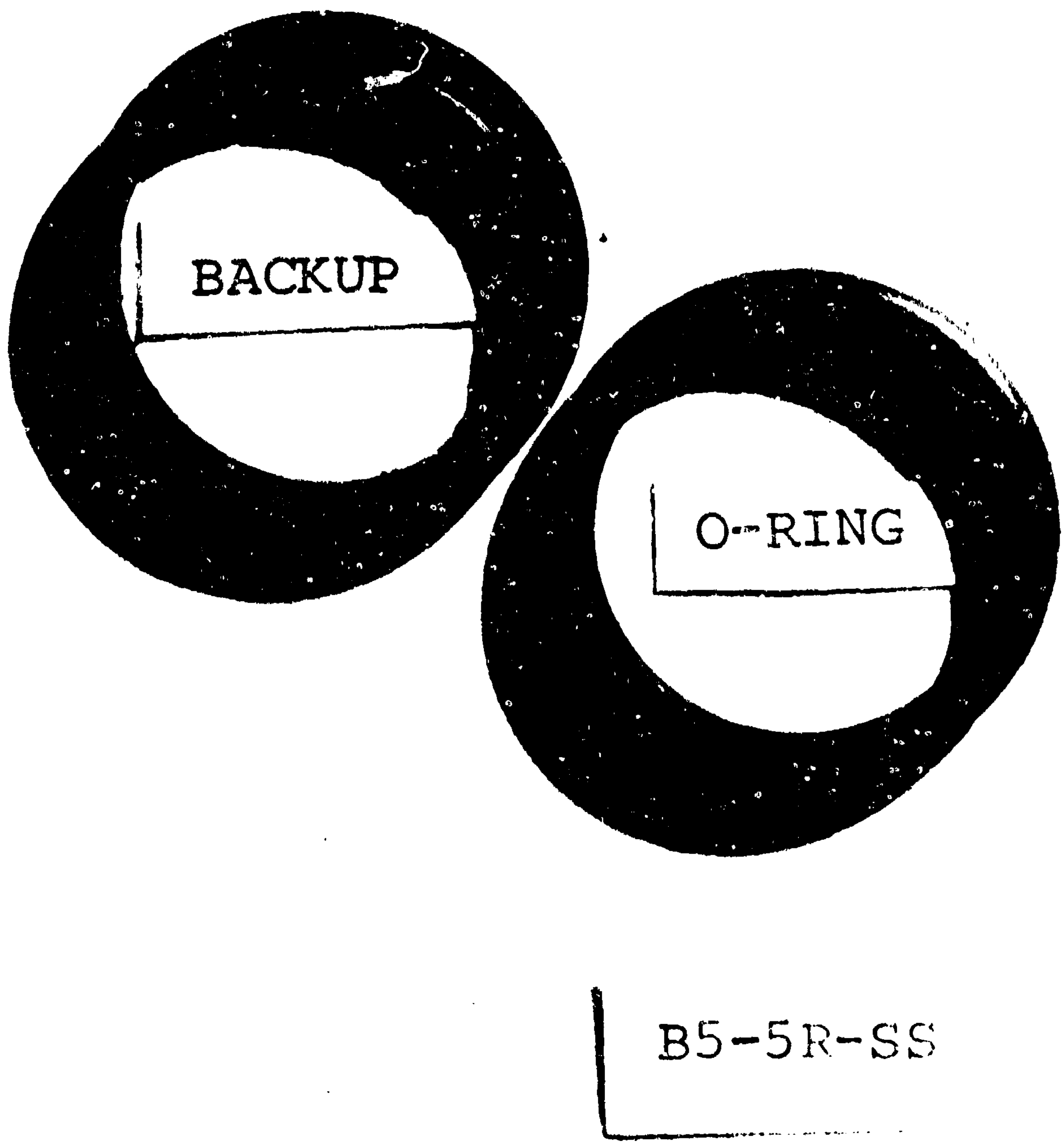


Figure 38. Candidate B5 After 3.30 x 10^6 Endurance Cycles With No Impulse Testing. O-ring condition is poor.

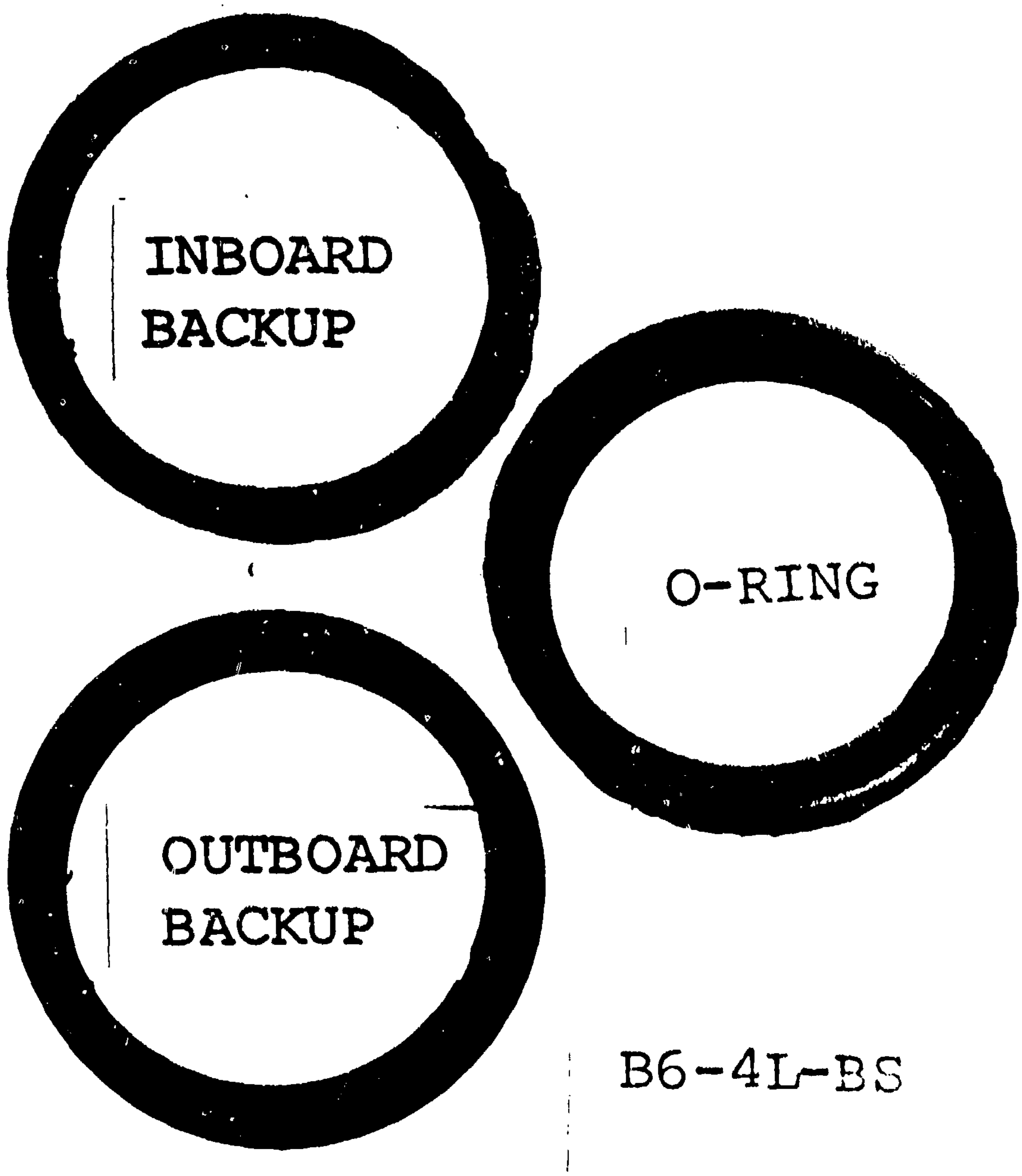


Figure 39. Candidate B6 After Backup Screening Test. Two stage backup has high wear on unfilled TFE inboard backup. O-ring condition is poor.

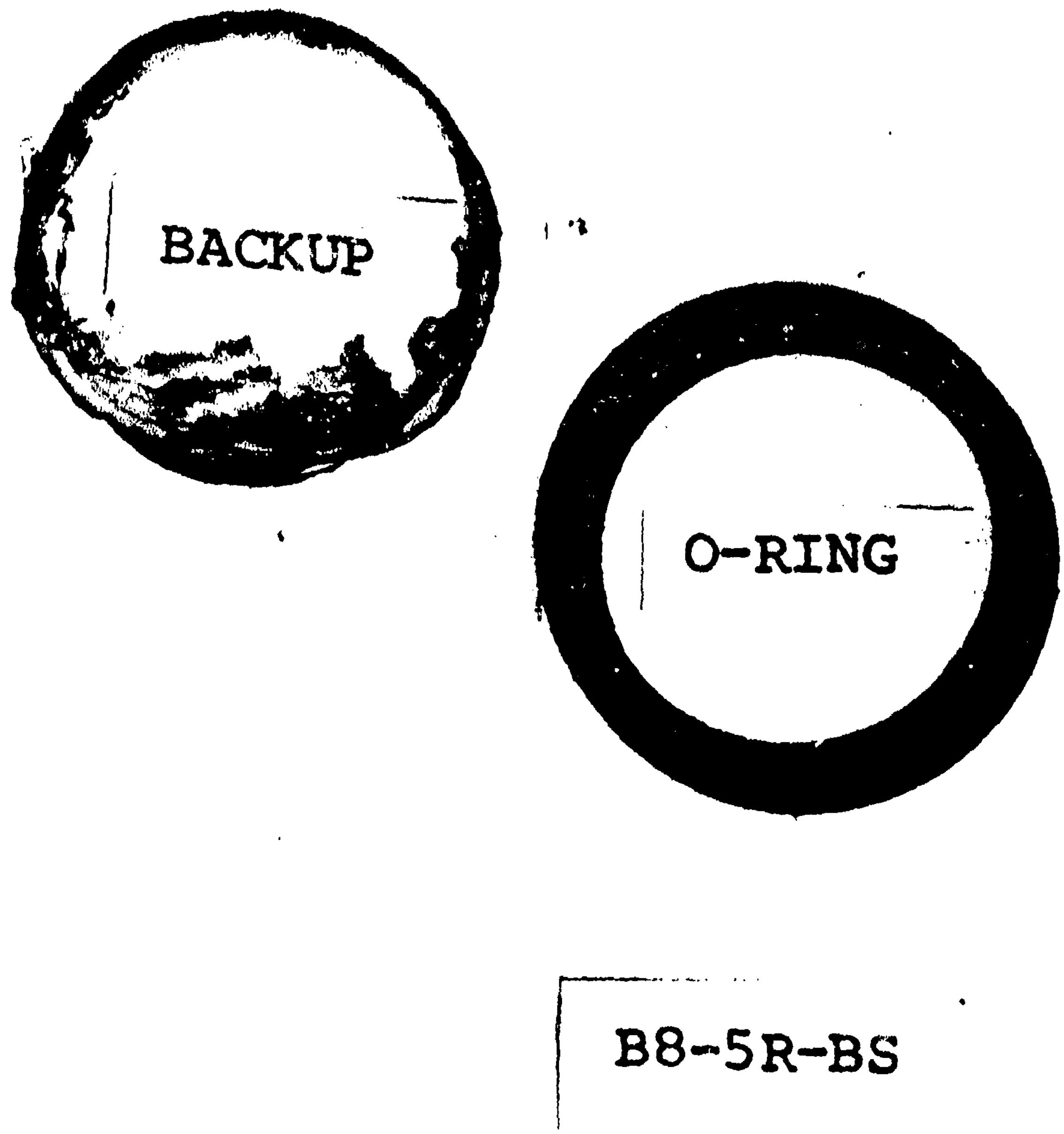


Figure 40. Candidate B8 After Backup Screening Test. Triangle shape backup of unfilled TFE has worn almost thru. O-ring condition is excellent.

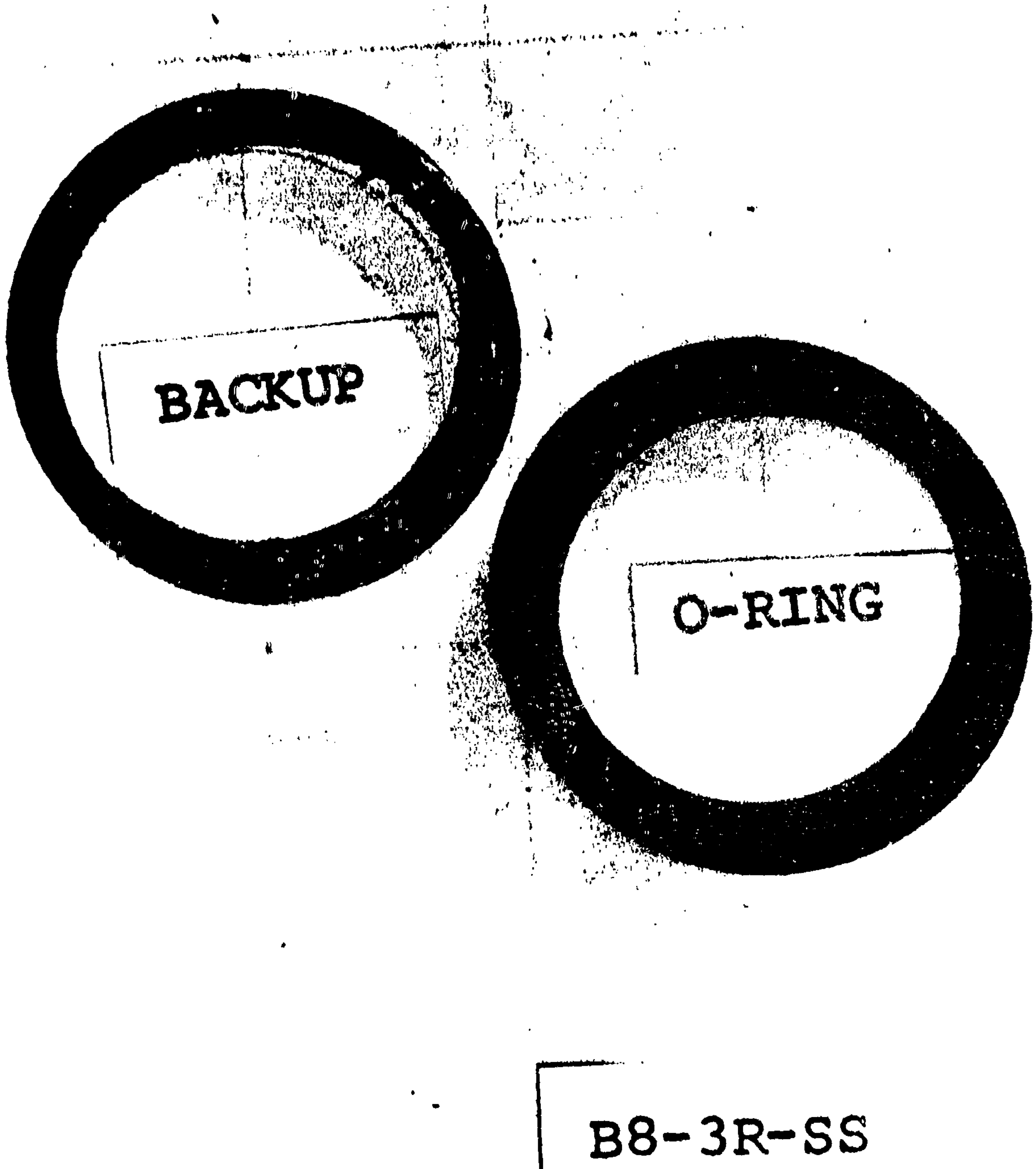


Figure 41. Candidate B8 After 3.30 x 10^6 Endurance Cycles with No Impulse Testing. O-ring condition is excellent. Compare wear of backup with Figure 40.

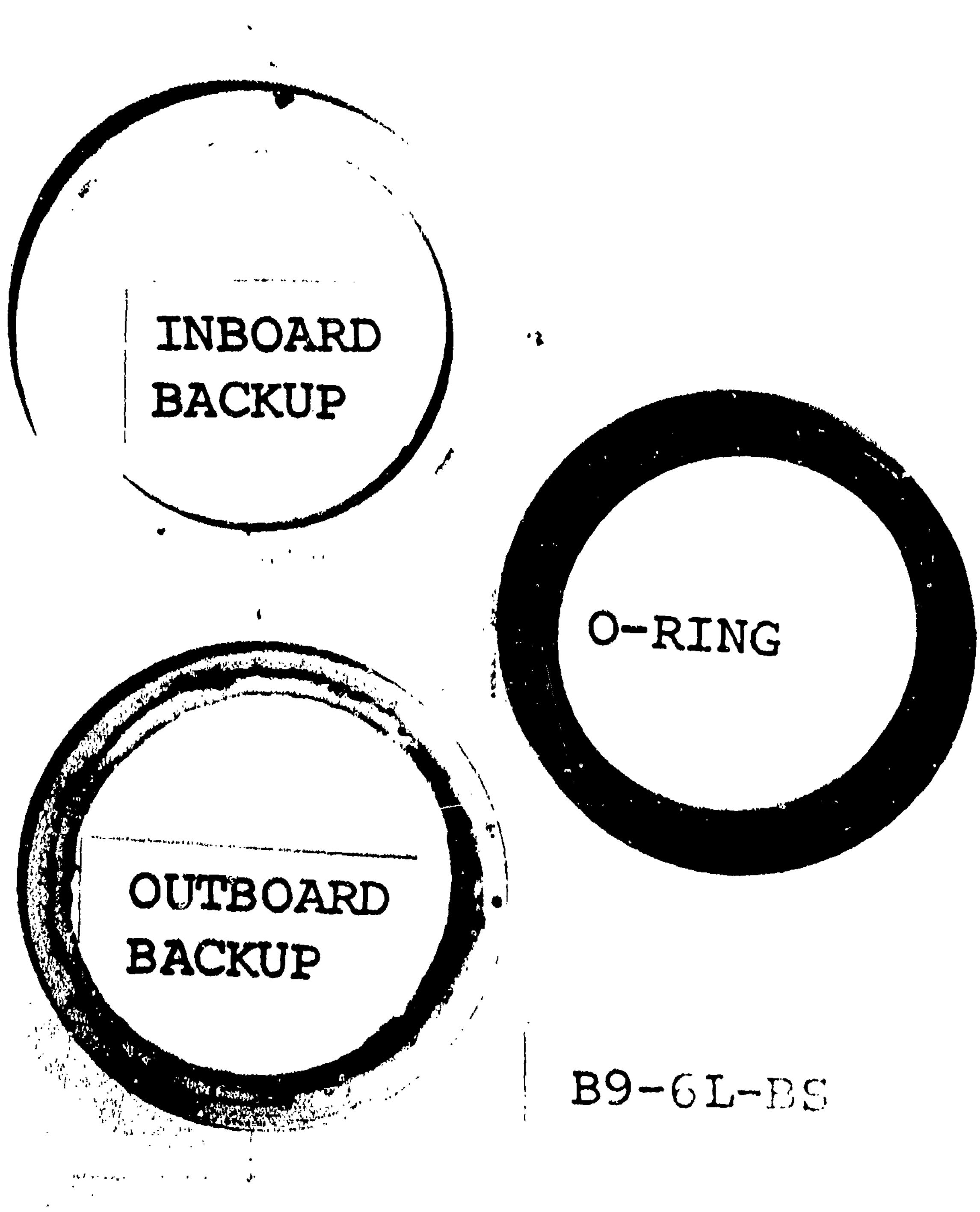


Figure 42. Candidate B9 After Backup Screening Test.
O-ring condition is excellent.

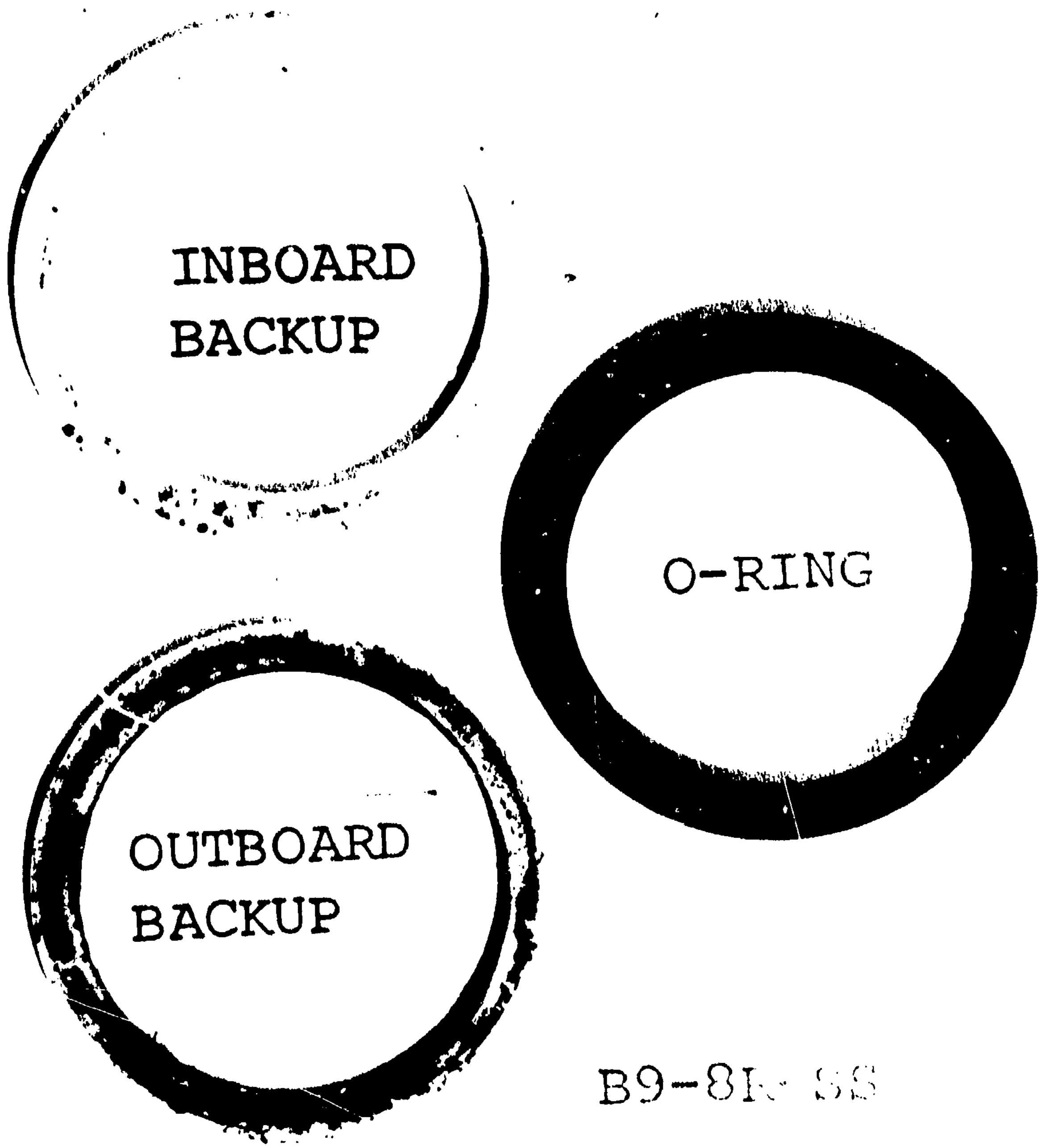


Figure 43. Candidate B9 After 3.30 x 10^6 Endurance Cycles With No Impulse Testing. O-ring condition is fair.

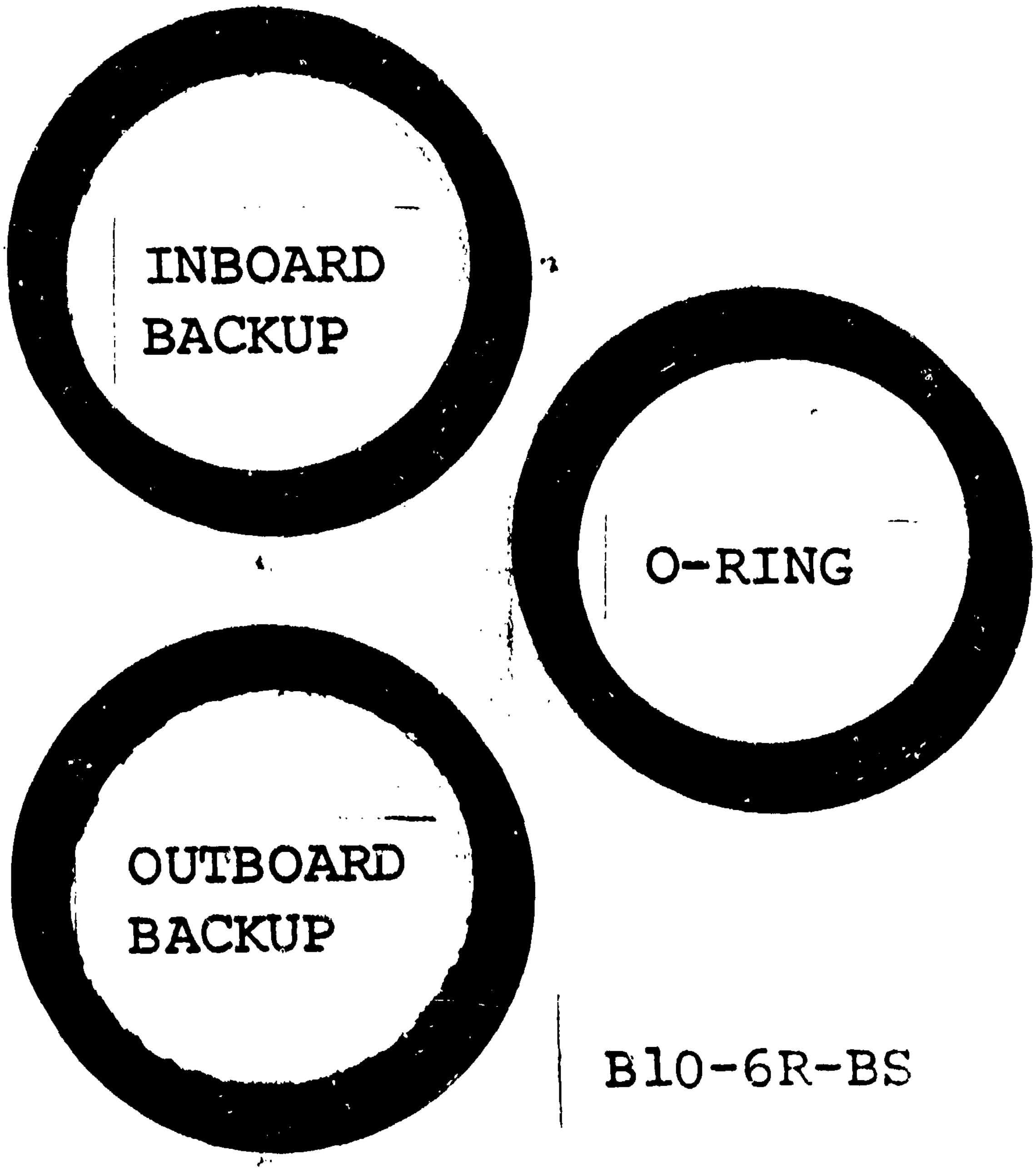


Figure 44. Candidate B10 After Backup Screening Test. Concave shape backup of Tetralon 720 has little wear. O-ring condition is poor with nibbling around the entire ID.

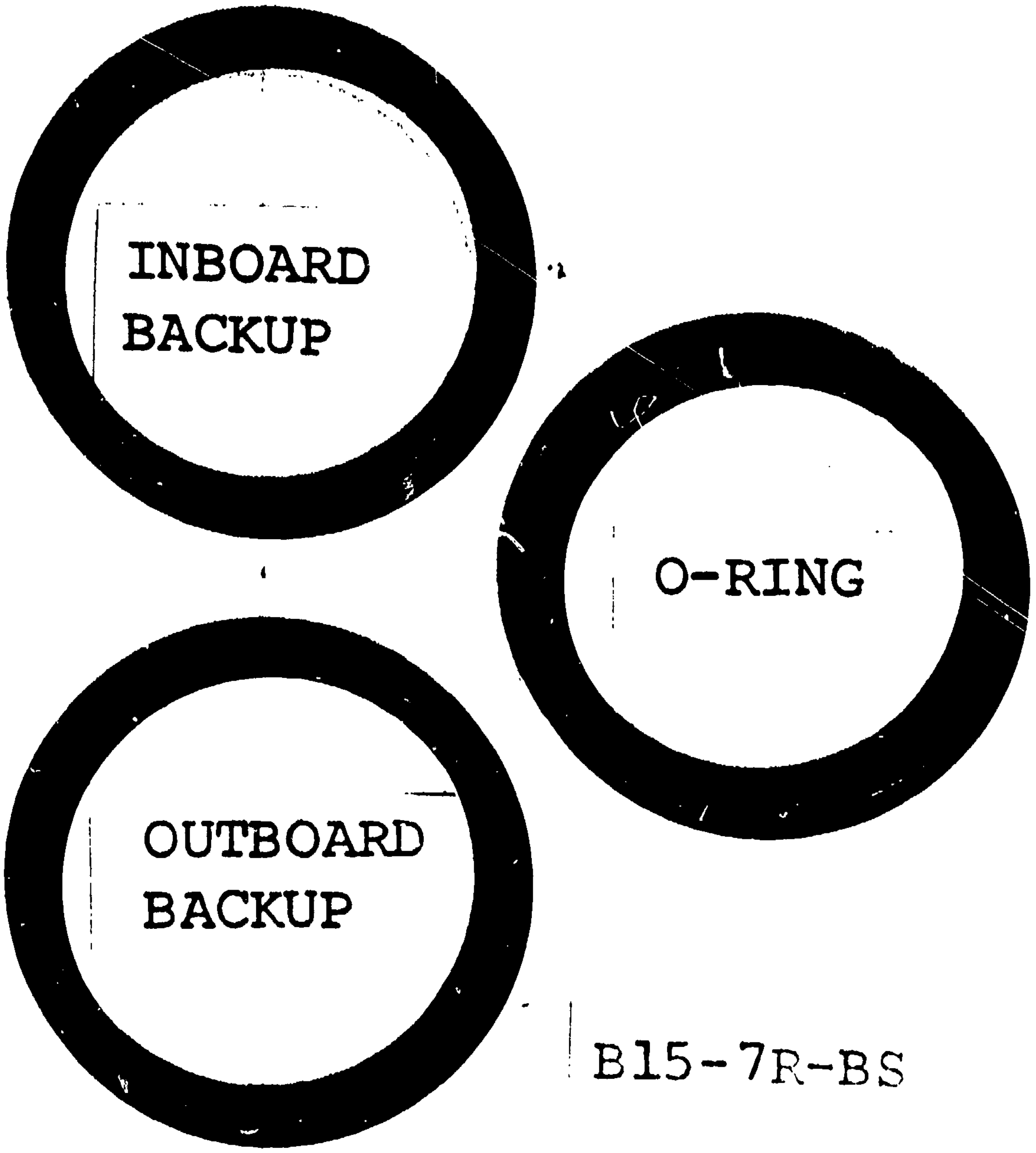


Figure 45. Candidate B15 After Backup Screening Test. O-ring suffered catastrophic failure due to rod scoring. Polyimide (SP-1) backups are undamaged. Exclusive of scoring damage, O-ring has severe nibbling around ID.

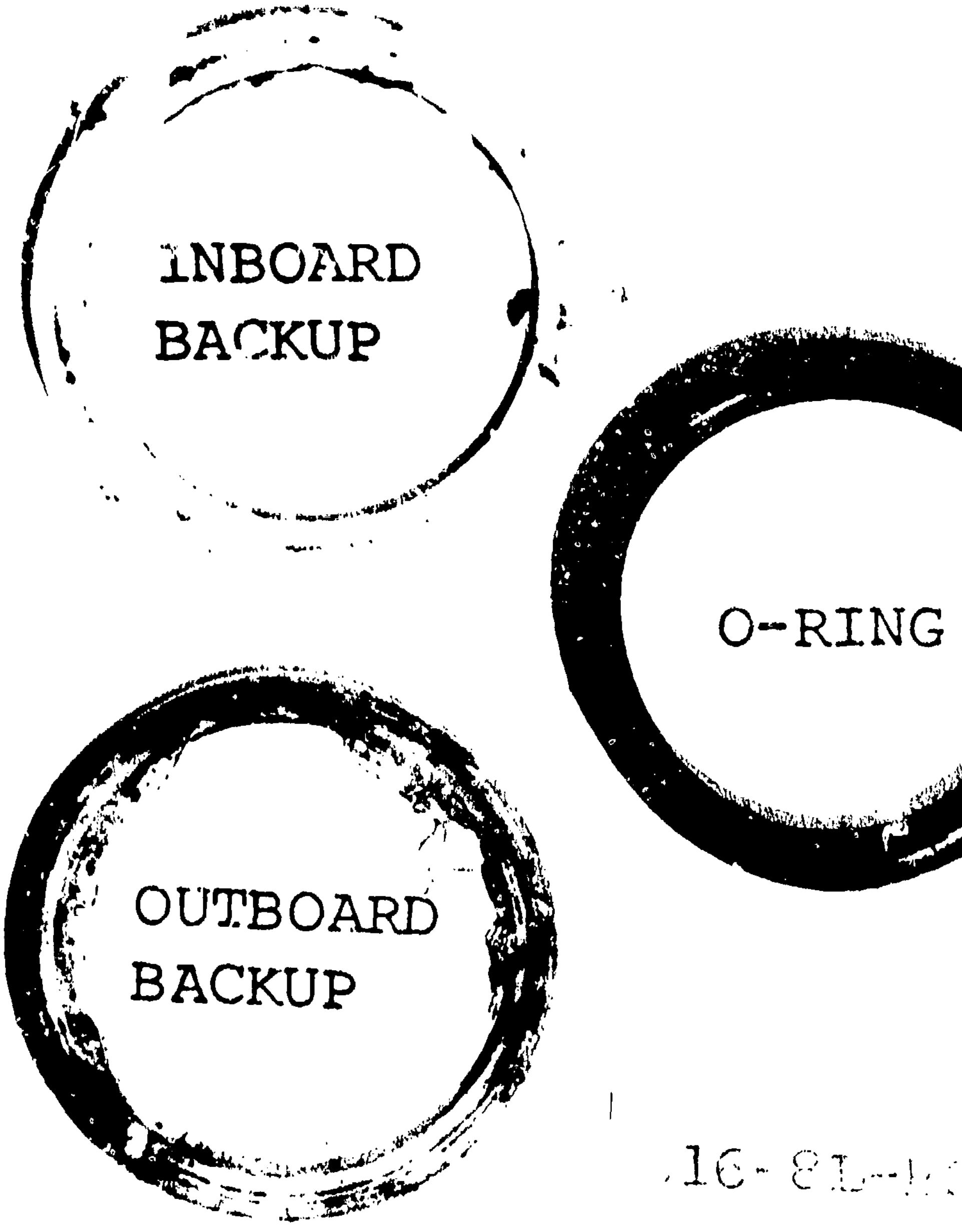


Figure 46. Candidate B16 After Backup Screening Test. O-ring has twisted, condition is fair.

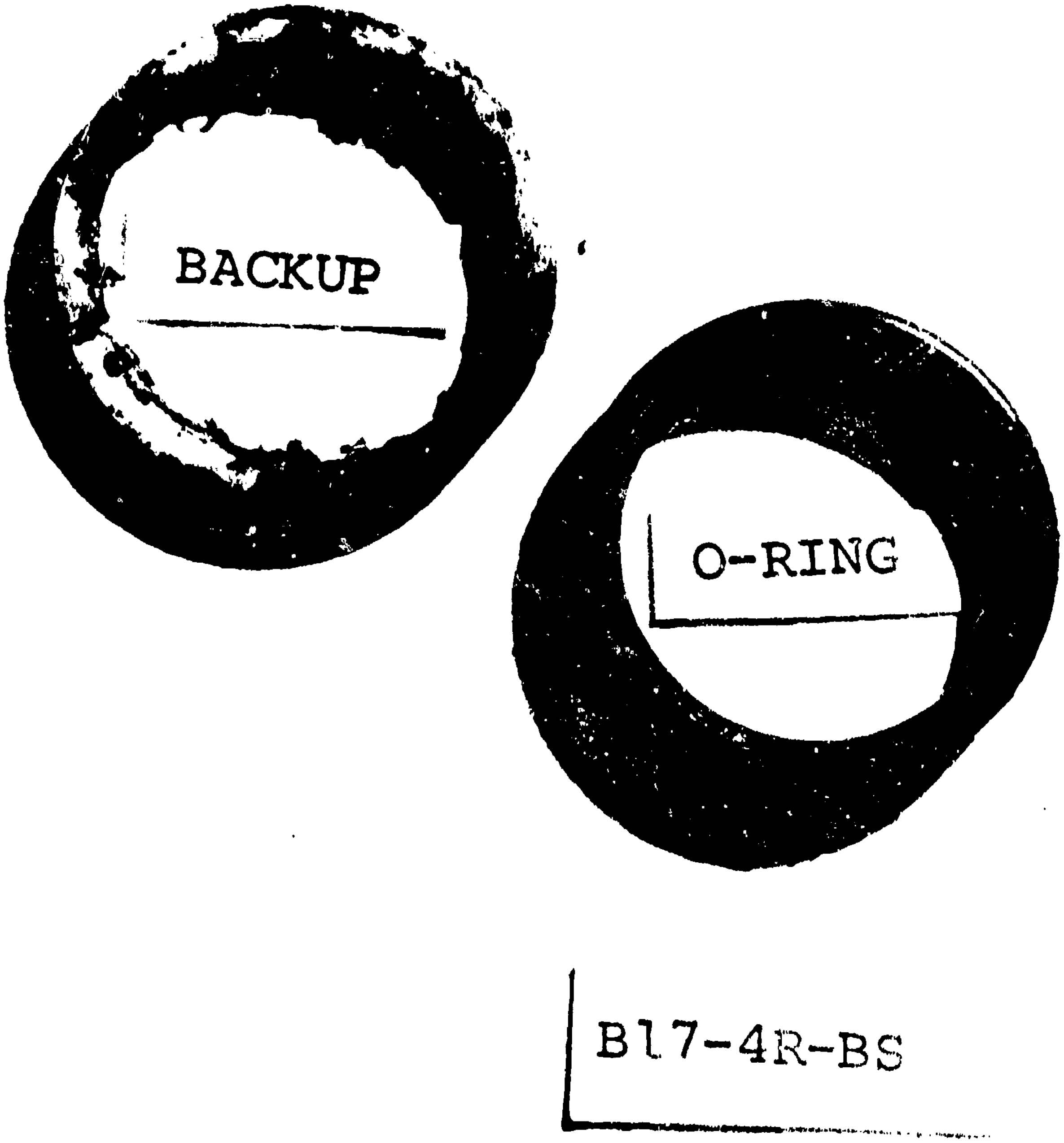


Figure 47. Candidate B17 After Backup Screening Test - Square Shape Backup. O-ring condition is poor.

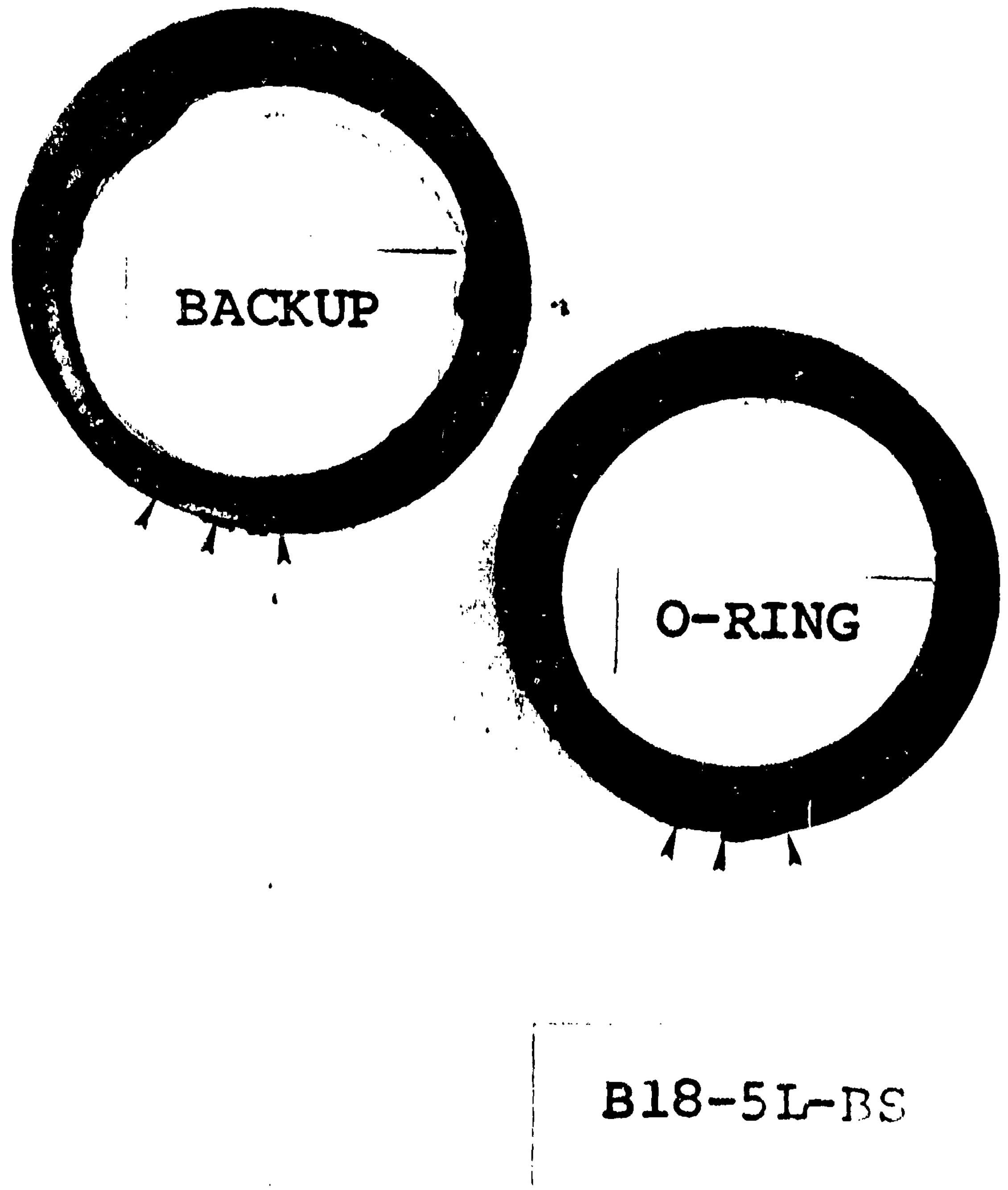


Figure 48. Candidate B18 After Backup Screening Test. Two stage backup of unfilled TFE had catastrophic failure at 1.43 x 10^6 cycles by O-ring extrusion on the OD. Arrows denote corresponding failure points on O-ring and backup.

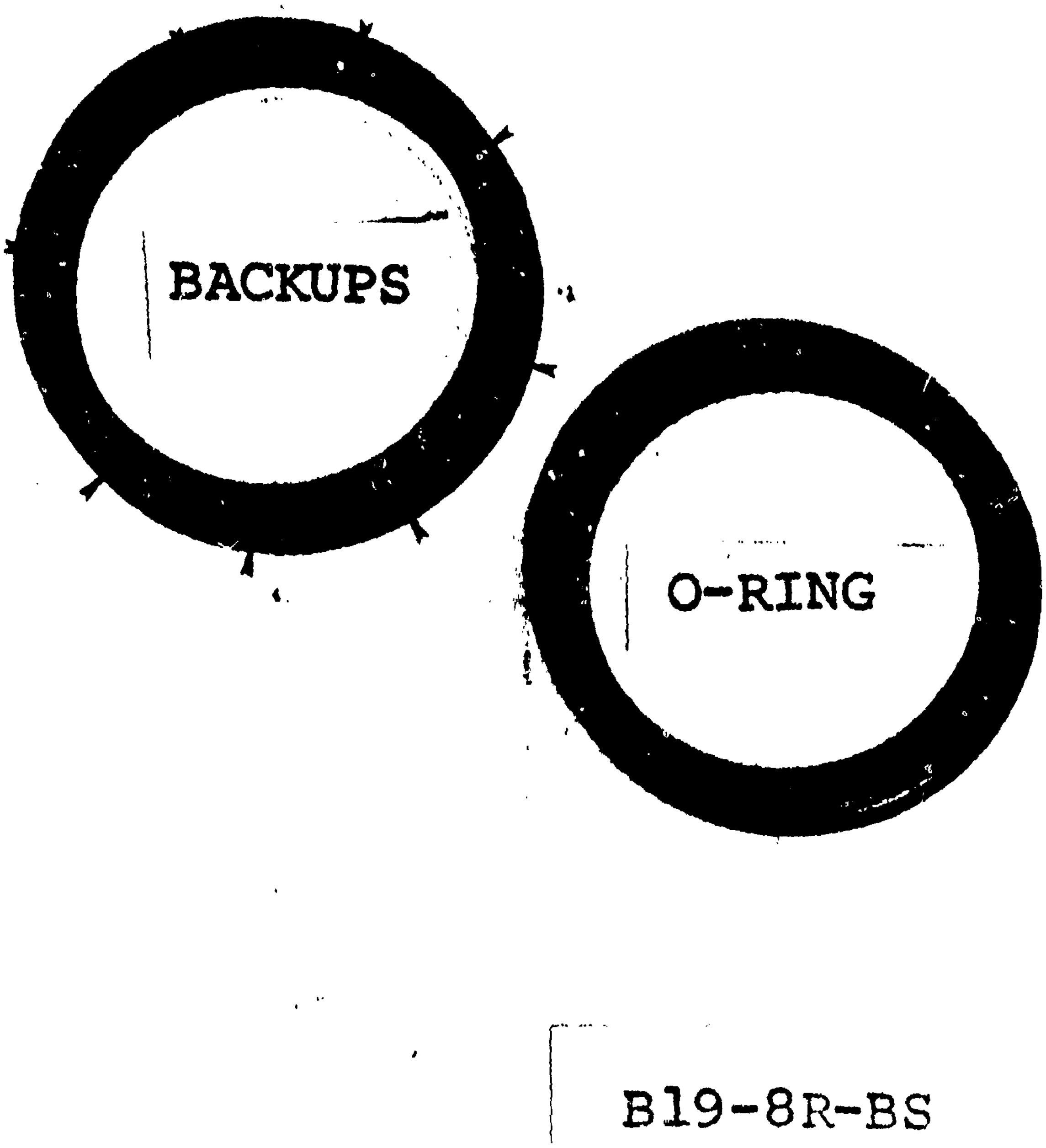


Figure 49. Candidate B19 After Backup Screening Test. Two stage backup with reduced OD polyimide outer backup; Tetralon 720 inner backup exhibits cold flow over the OD of the center backup (see arrows). O-ring condition is fair.

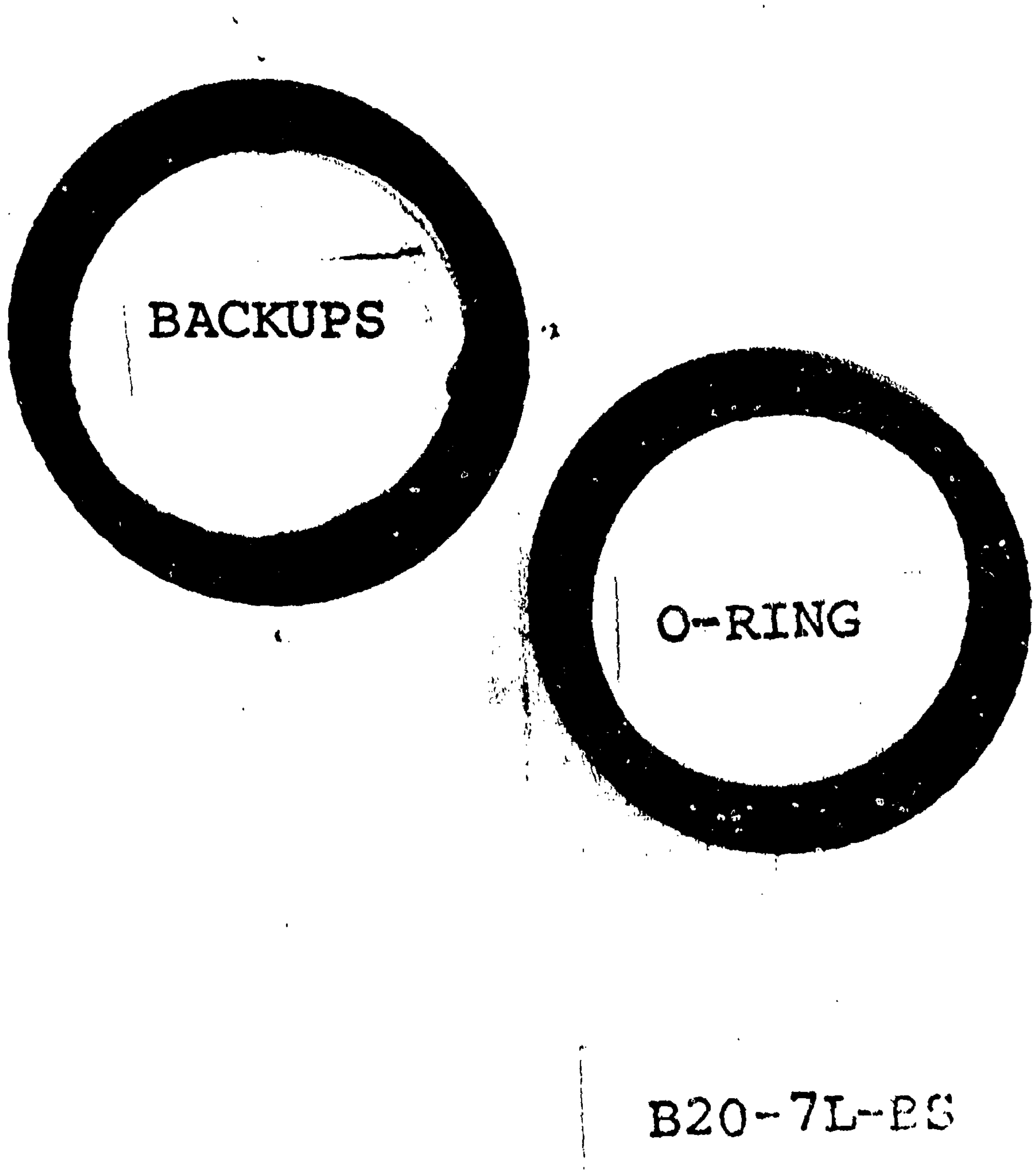


Figure 50. Candidate B20 After Backup Screening Test. Two stage backup of spiral backups. O-ring condition is excellent.

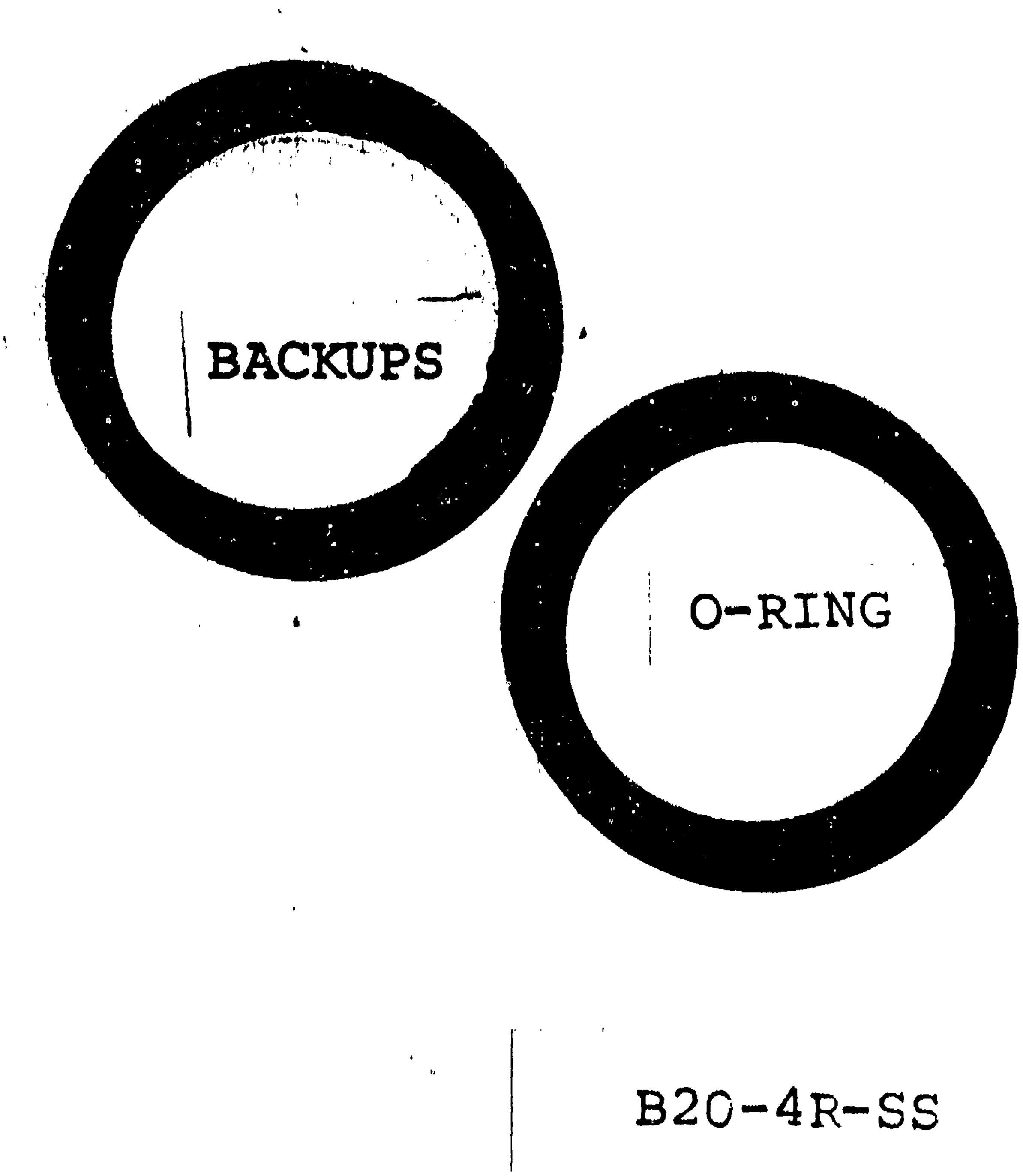


Figure 51. Candidate B20 After 3.30 x 10^6 Endurance Cycles with No Impulse Testing. O-ring condition is good. Two stage backups are fused together.

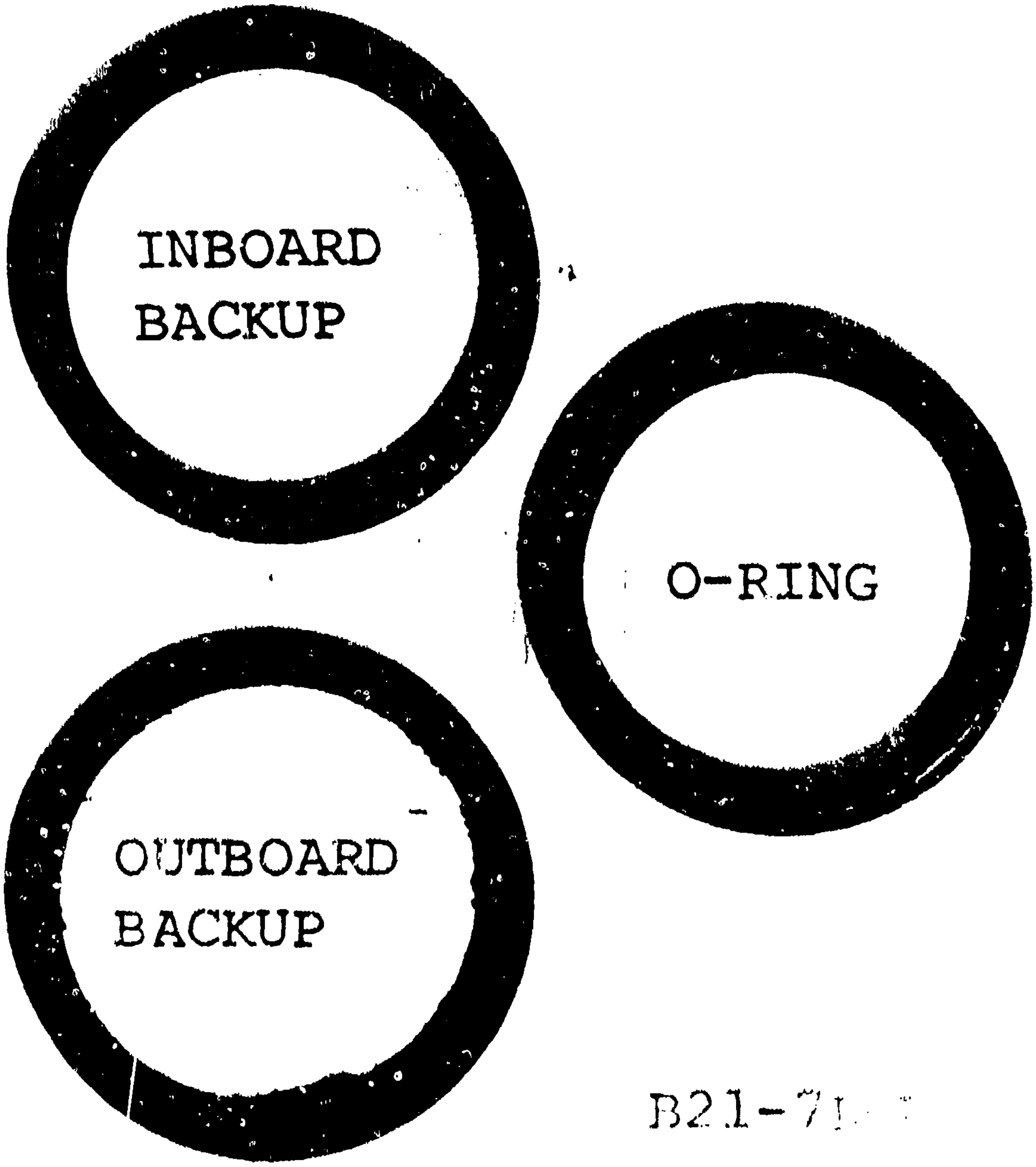


Figure 52. Candidate B21 After Backup Screening Test. O-ring condition is poor.

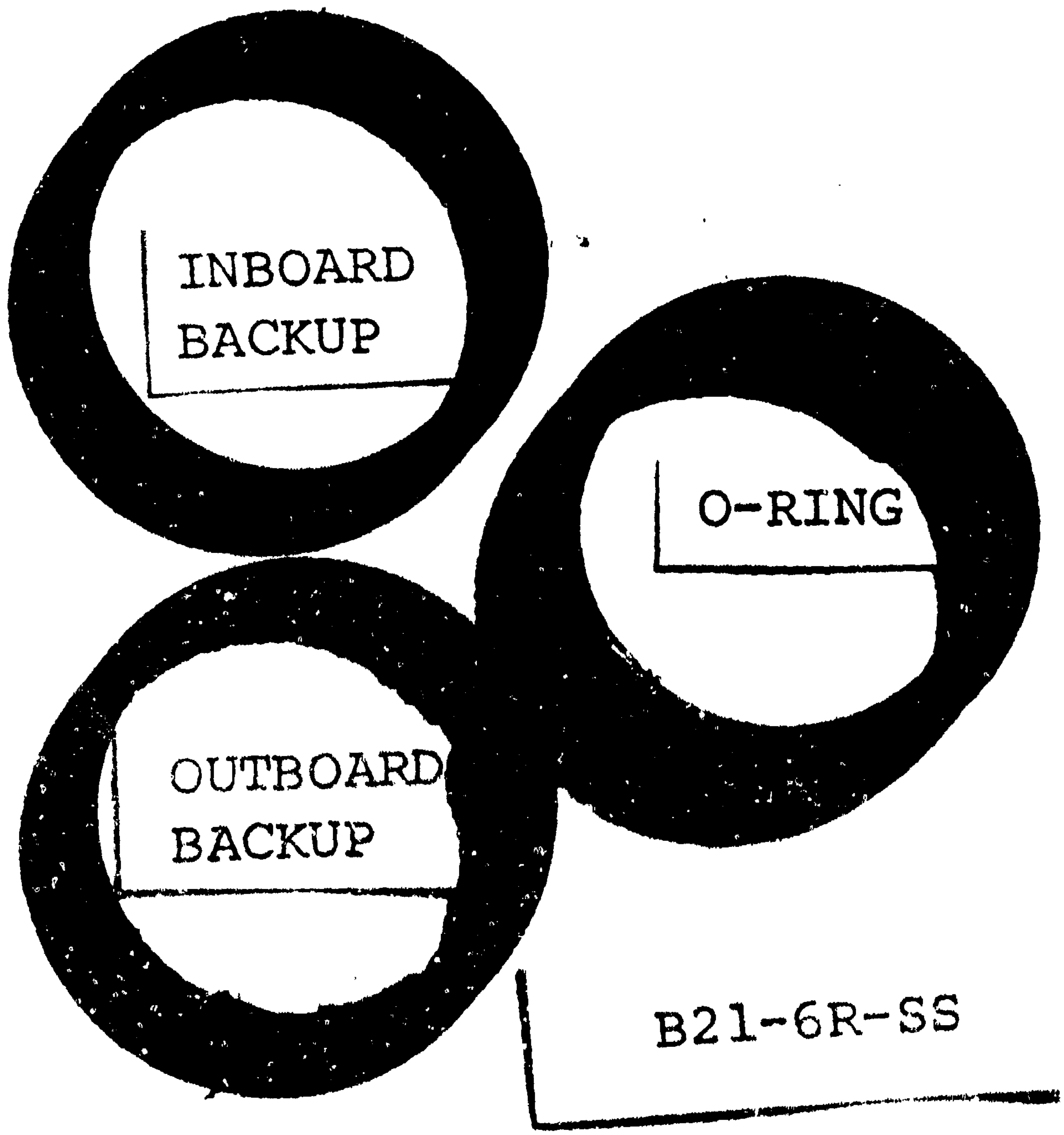


Figure 53. Candidate B21 After 3.30 x 10^6 Endurance Cycles With No Impulse Testing. O-ring condition is poor.

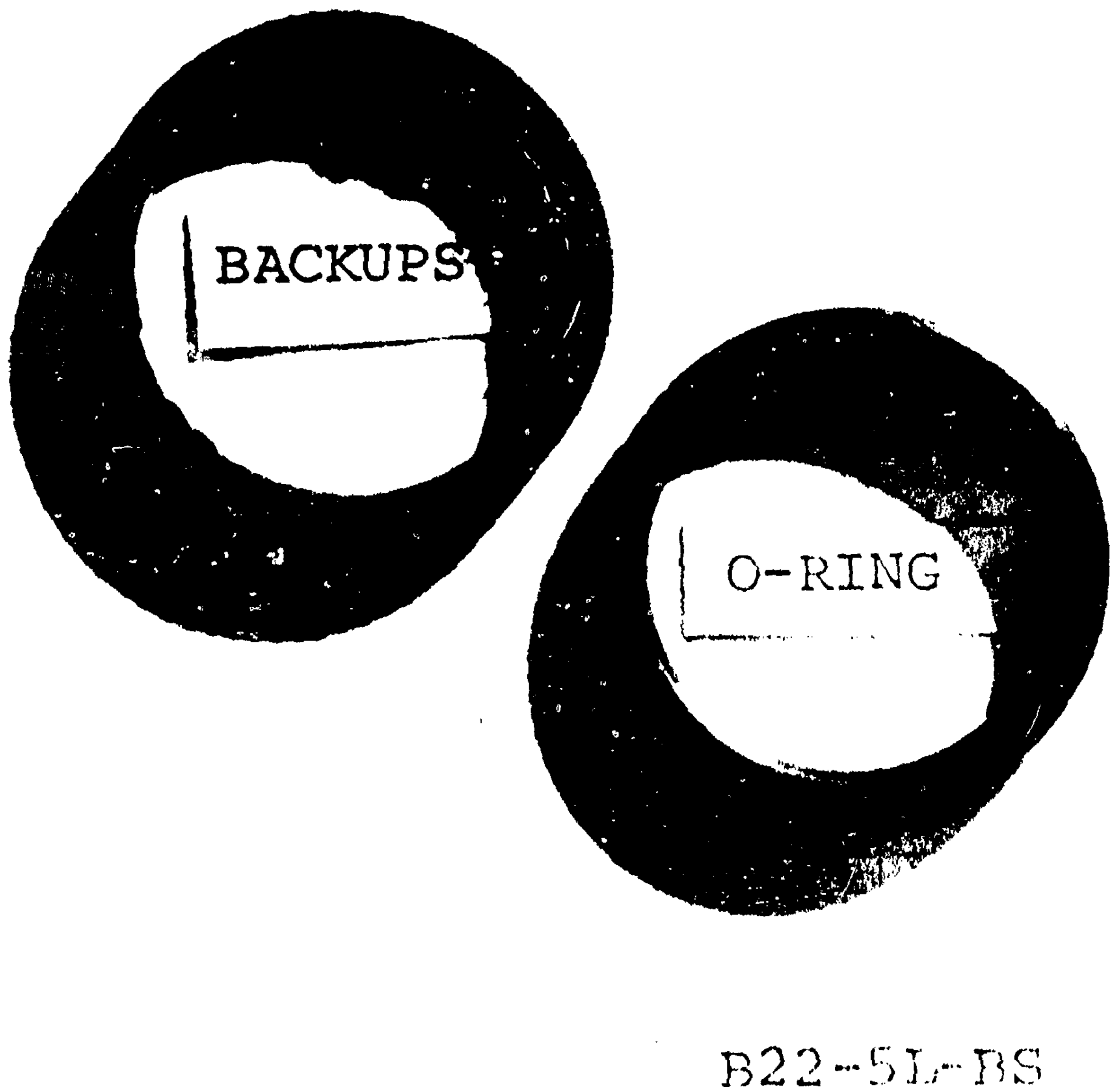


Figure 54. Candidate B22 After Backup Screening Test. Two stage backup of Revonoc 18158 has fused together. O-ring condition is excellent.

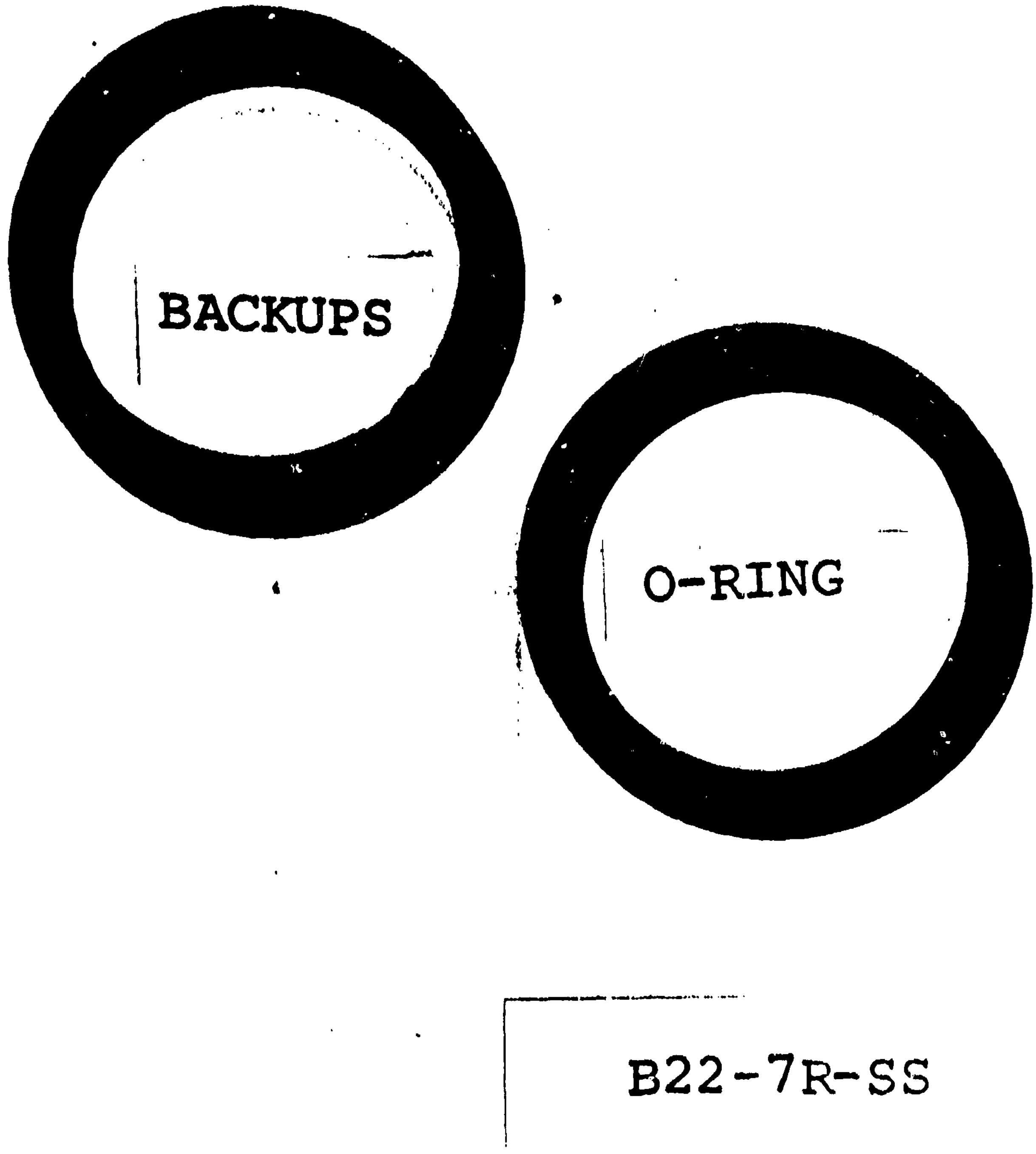


Figure 55. Candidate B22 After 3.30 x 10^6 Endurance Cycles With No Impulse Testing. O-ring condition is excellent.

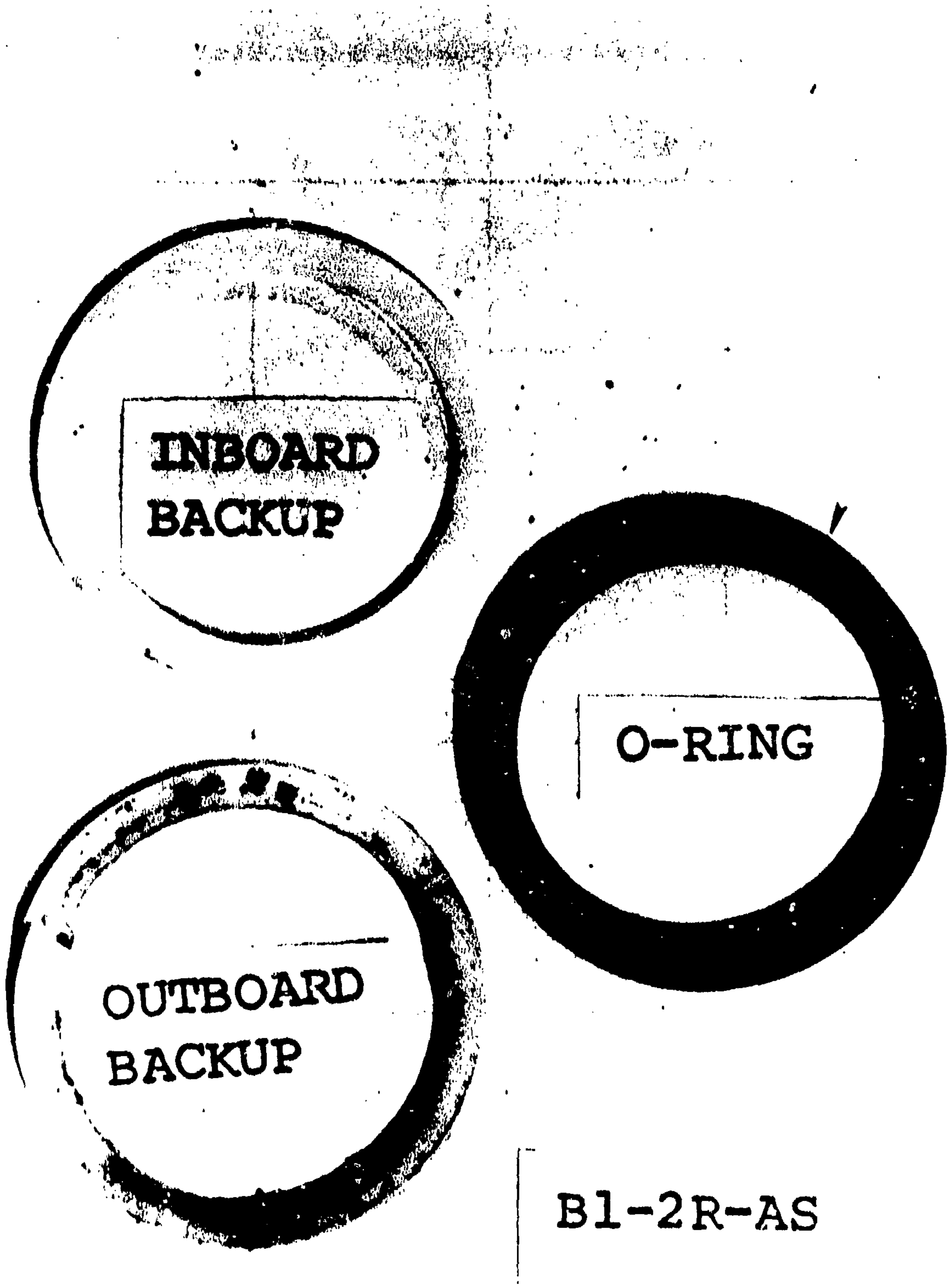


Figure 56. Candidate B1 Backup After Additional Screening Test. Suffered catastrophic failure after 2.08 x 10^6 endurance plus 86014 impulse cycles. Arrow denotes severe nibbling on O-ring.

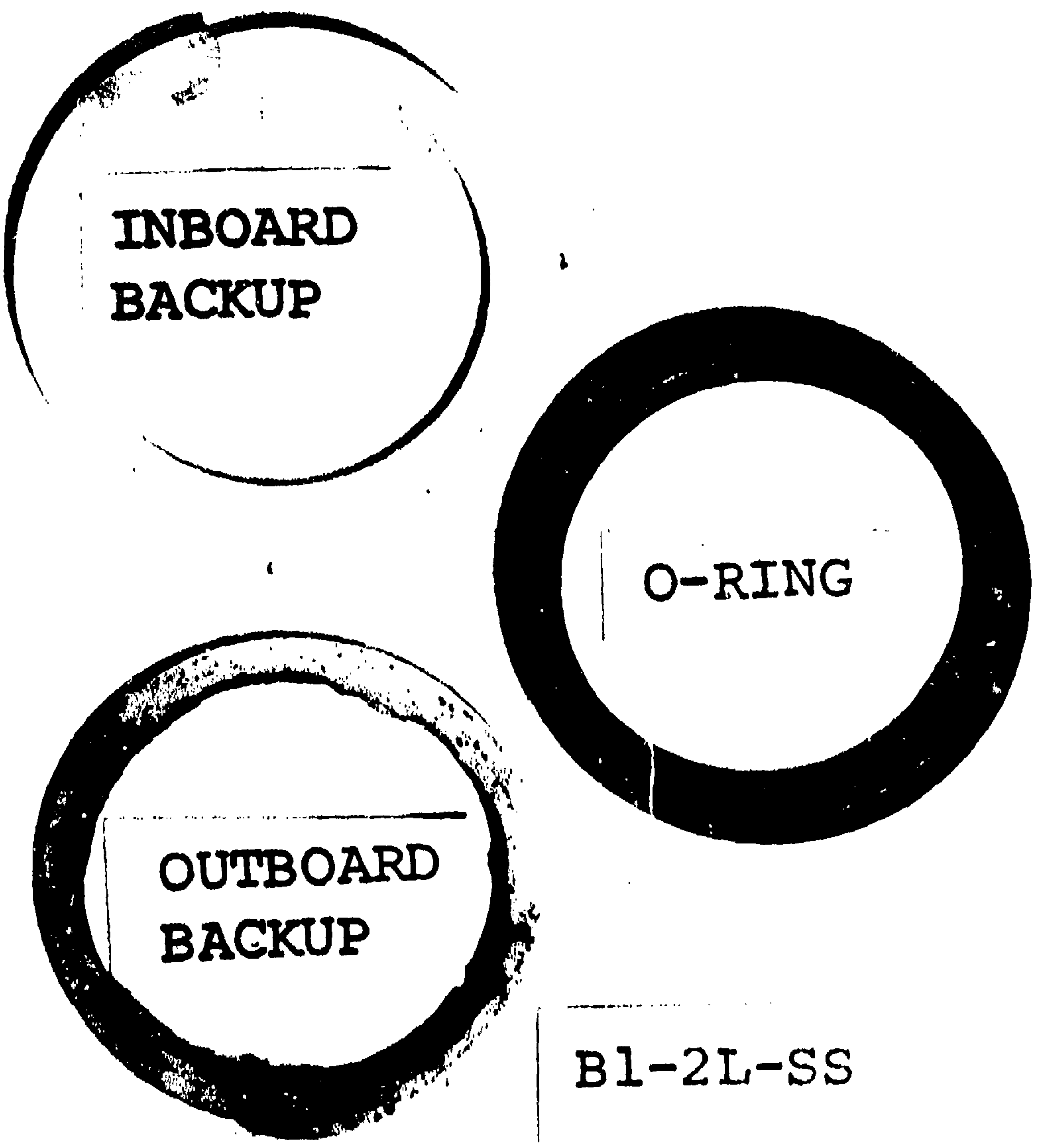


Figure 57. Typical Appearance of MS28774-214 Backups and M83461/1 O-ring Used With Scraper Candidates - No Impulse Testing. O-ring condition was good for 6 of 8 seals.

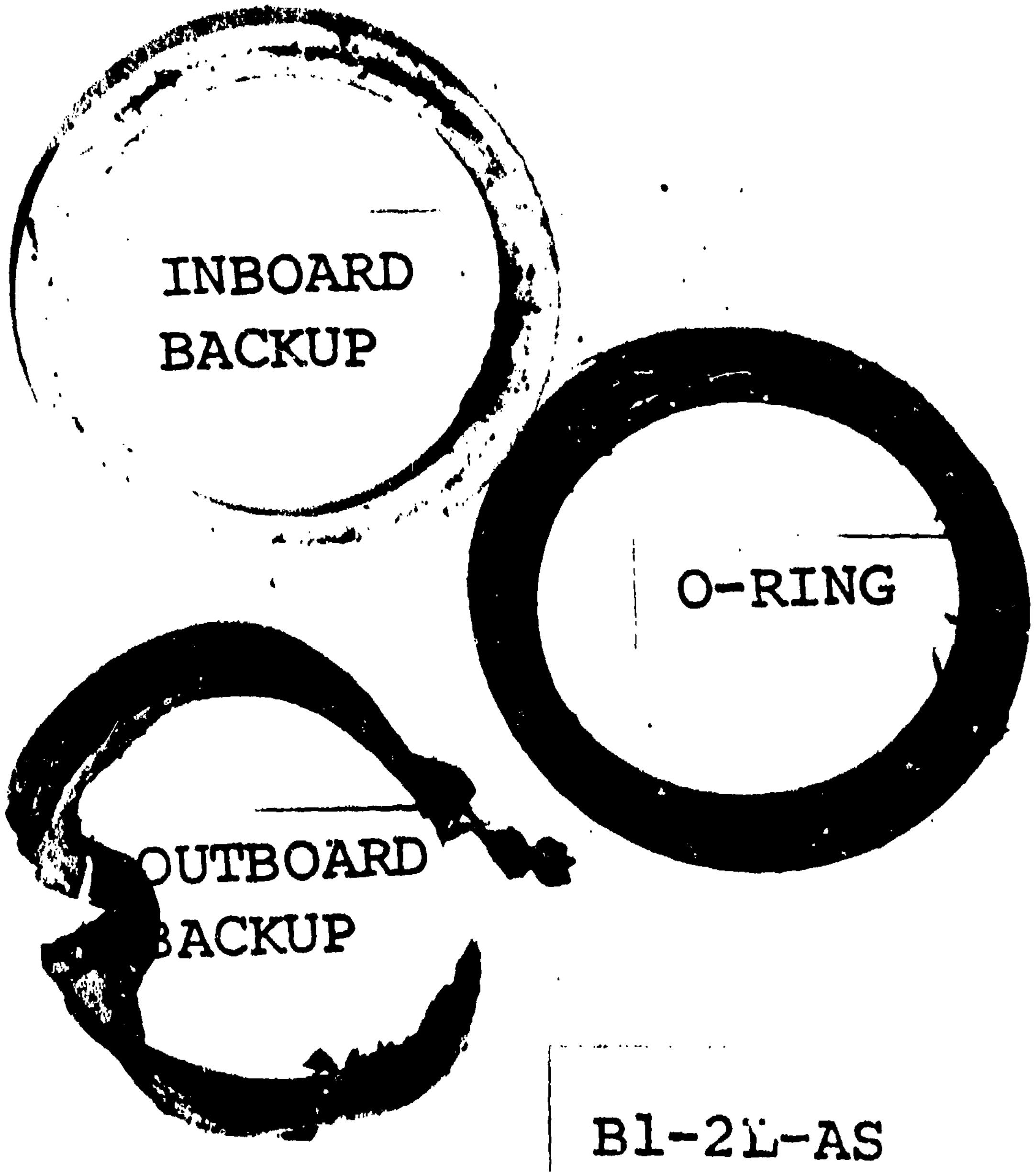


Figure 58. Typical Appearance of MS28774-214 Backups and M83461/1-214 O-ring Used With Scraper Candidates - With Impulse Testing. This seal is typical of the seven MS28774-214/M83461/-214 rod seals used with the scraper candidates during the Additional Screening Tests. Compare with Figure 57 which did not have impulse testing.

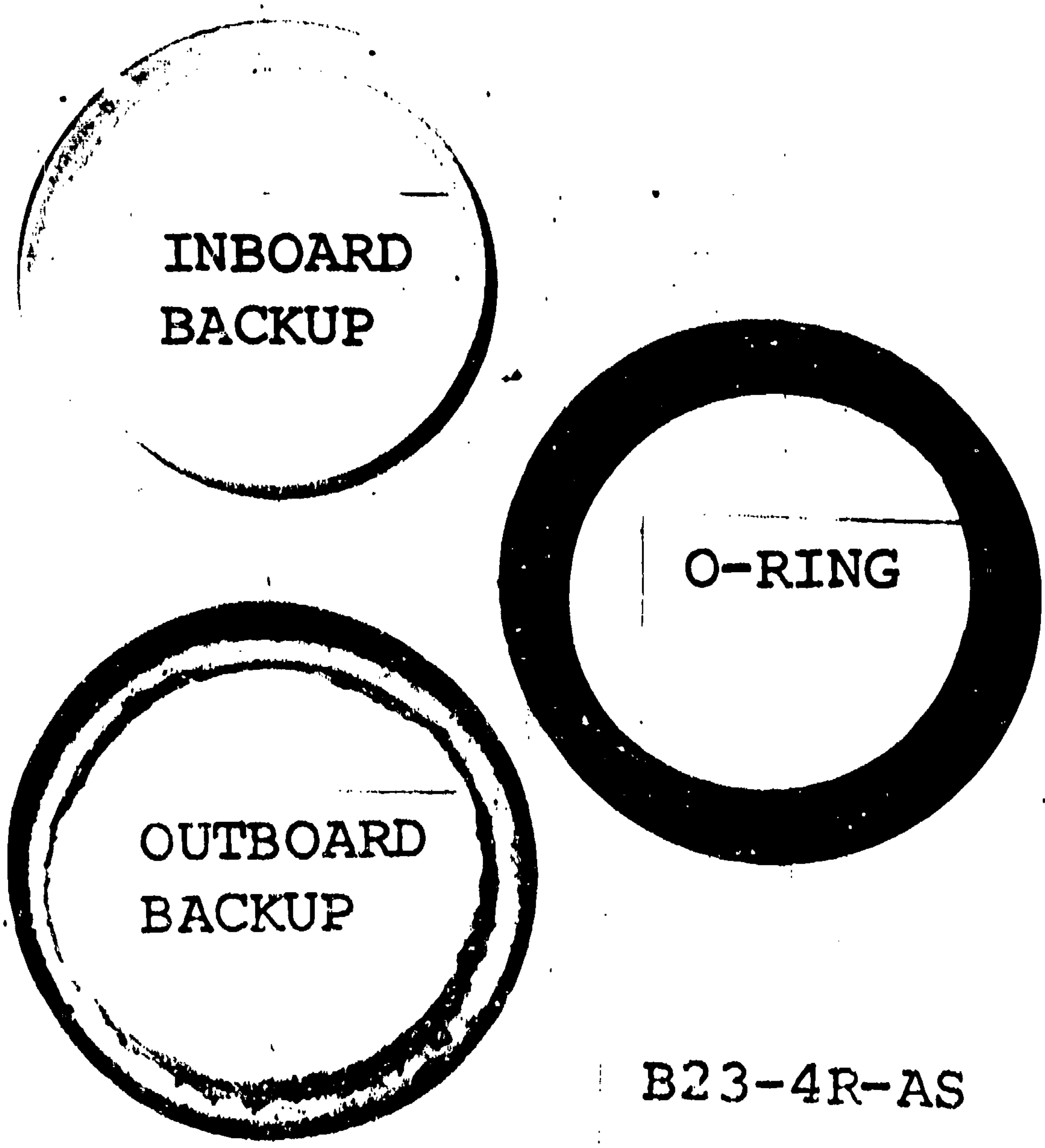


Figure 59. Candidate B23 Backup After Additional Screening Test. O-ring condition is excellent.

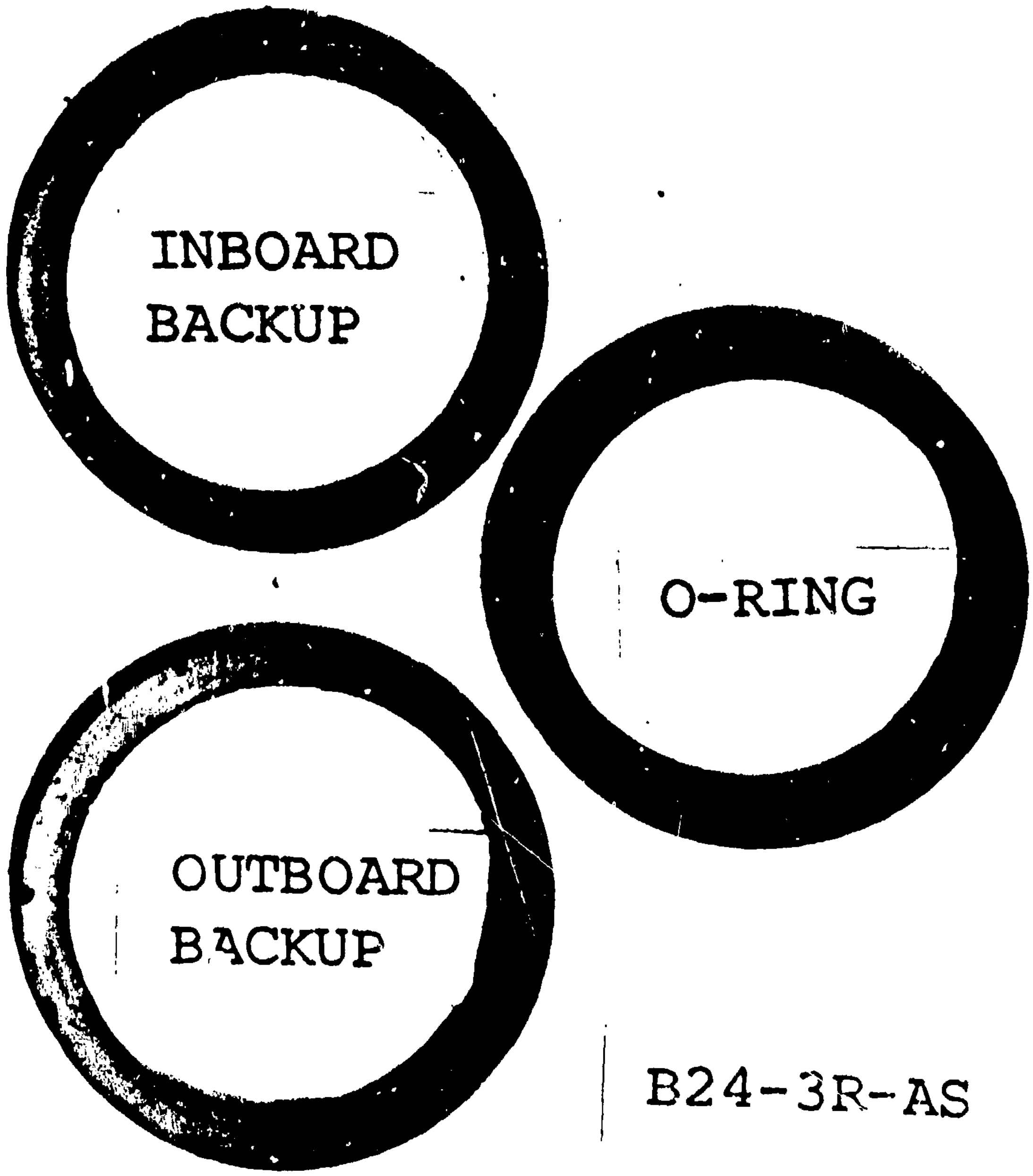


Figure 60. Candidate B24 Backup After Additional Screening Test. O-ring condition is good. Zero leakage was recorded.

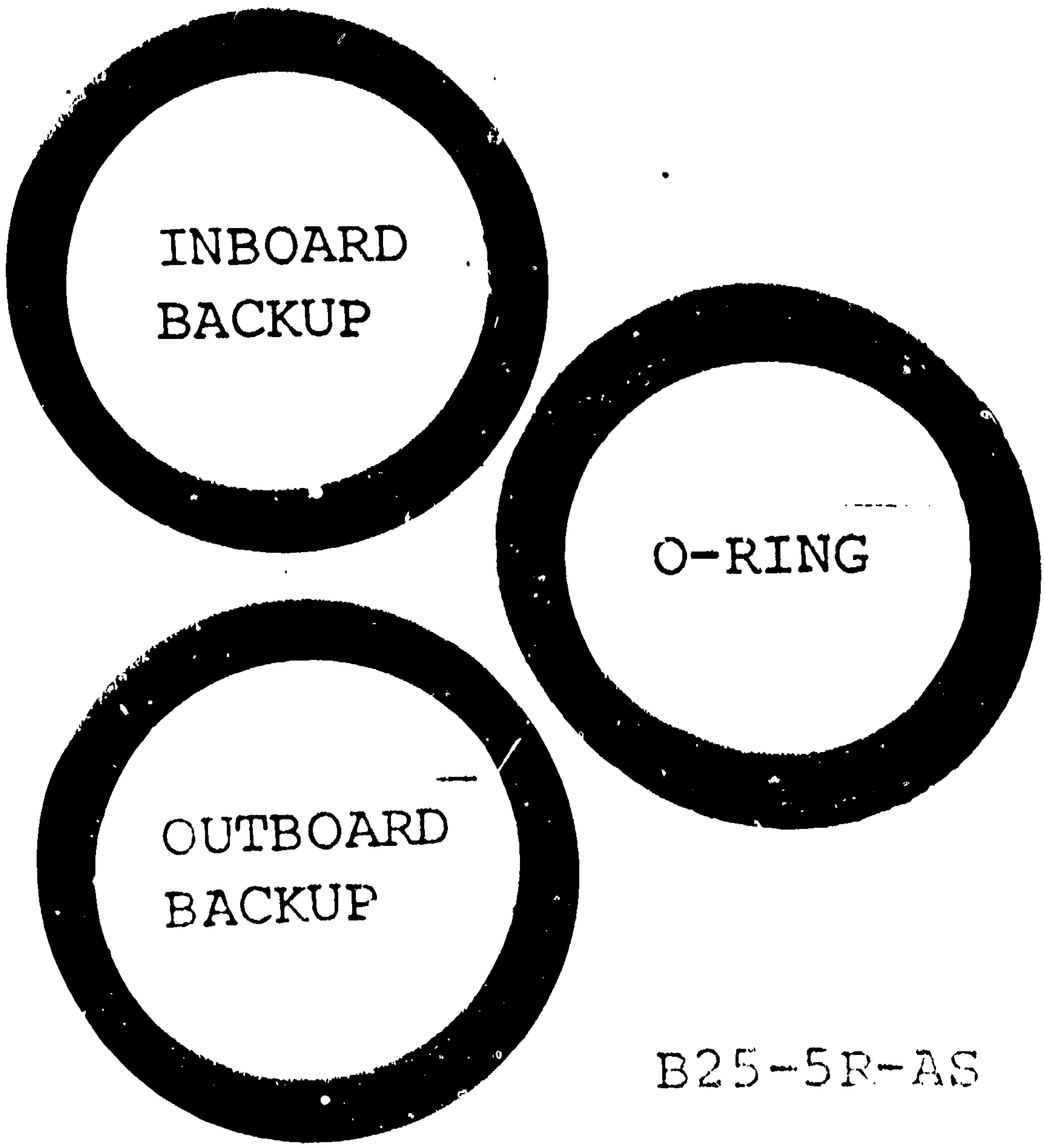


Figure 61. Candidate B25 Backup After Additional Screening Test. O-ring is severely nibbled and has rolled.

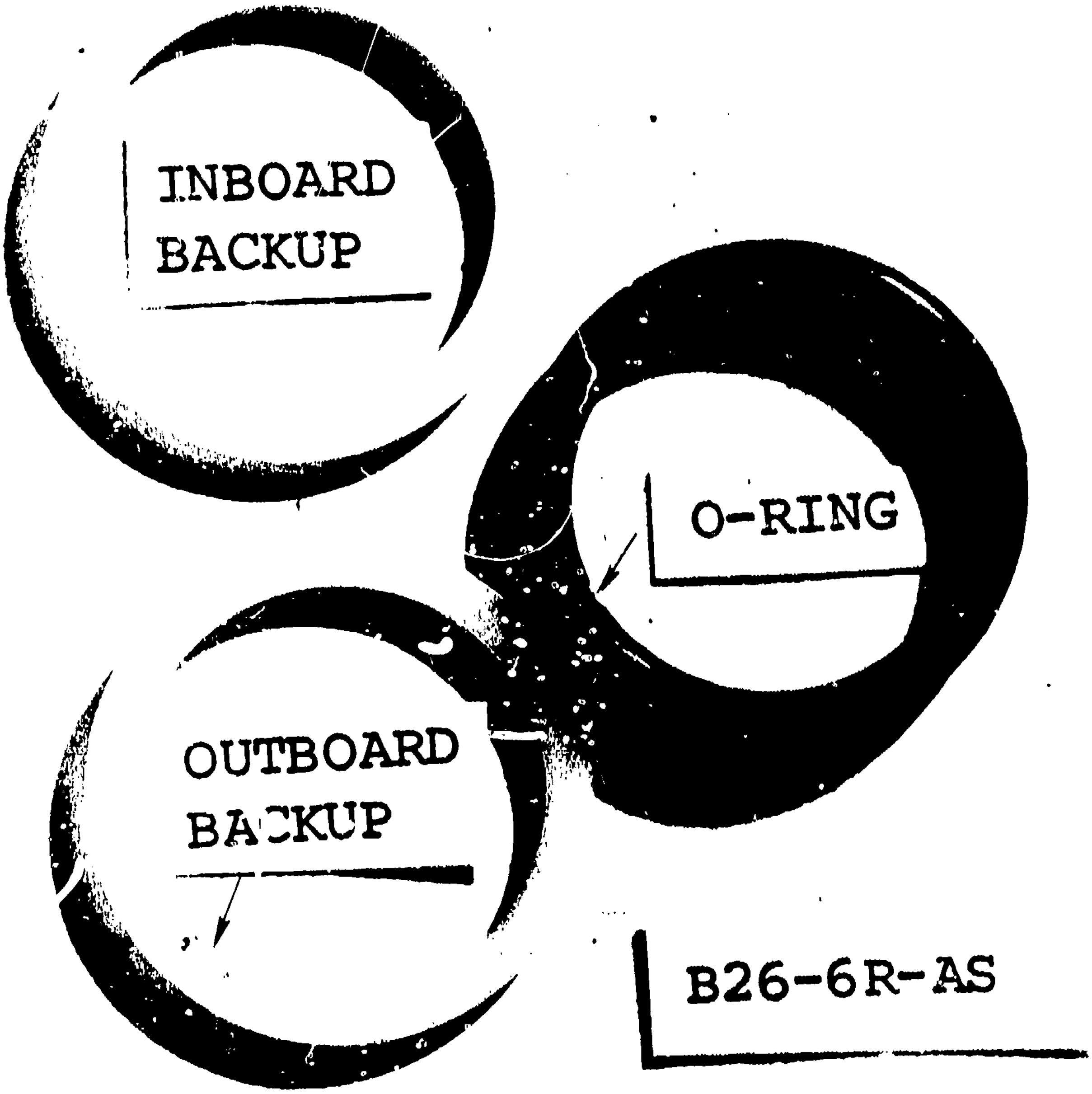


Figure 62. Candidate B26 Backup After Additional Screening Test. Removed when rod scored at 242997 endurance cycles. Arrow denotes damage due to scoring. O-ring is nibbled around ID.

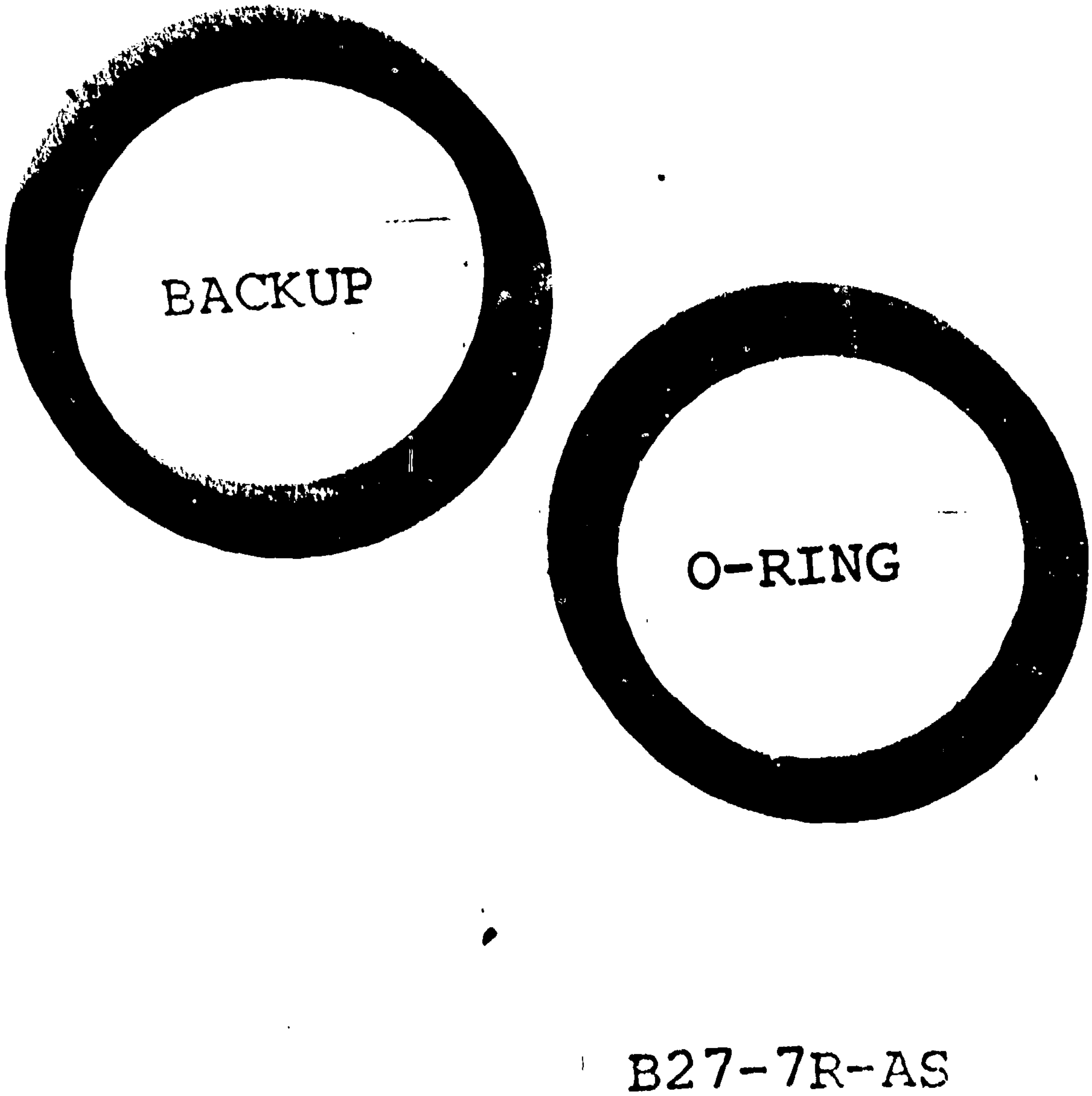


Figure 63. Candidate B27 Backup After Additional Screening Test. O-ring failed due to extrusion on the ID after 1.53 x 10^6 endurance plus 66000 impulse cycles.

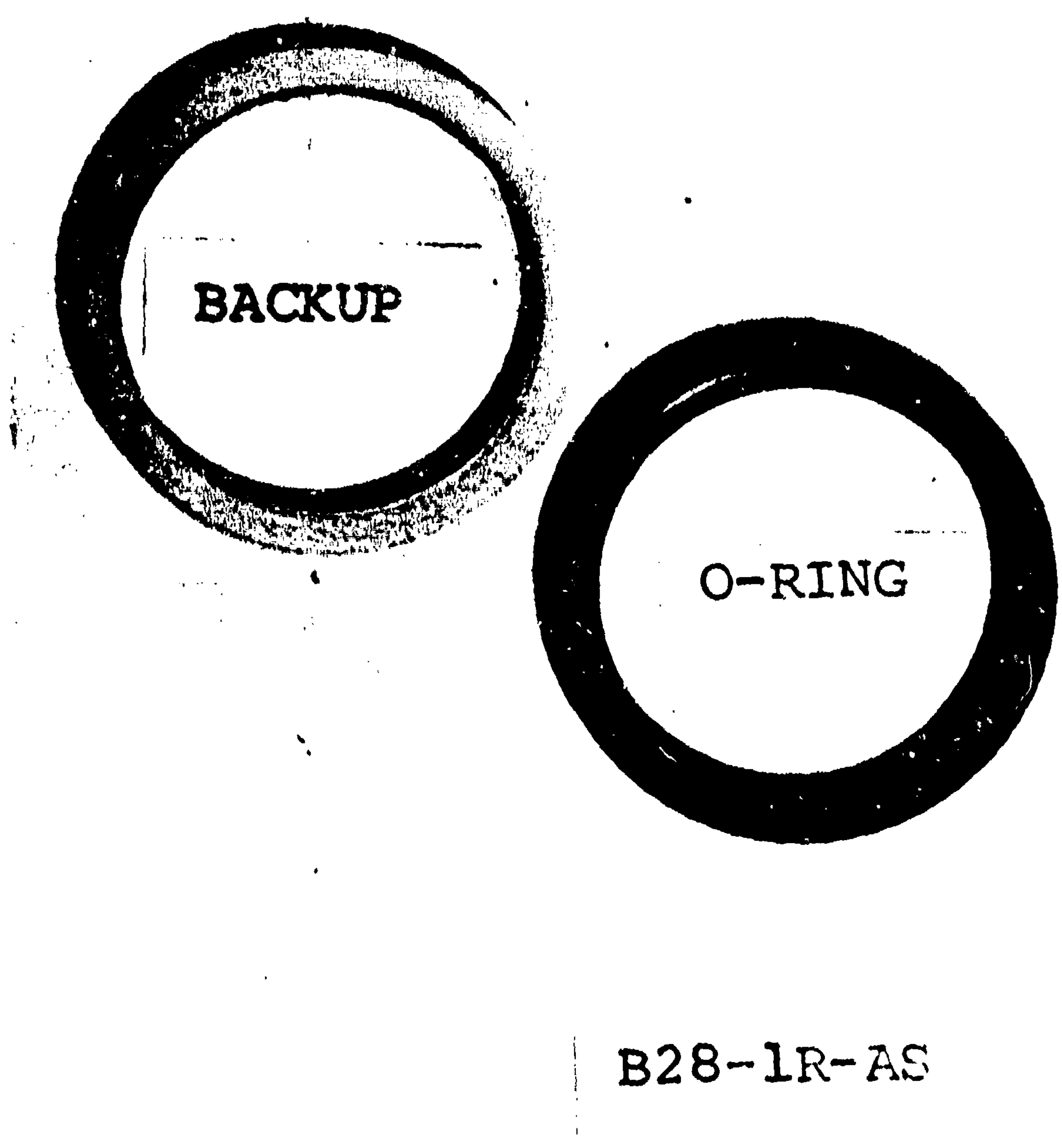


Figure 64. Candidate B28 Backup After Additional Screening Test. O-ring is in good condition.

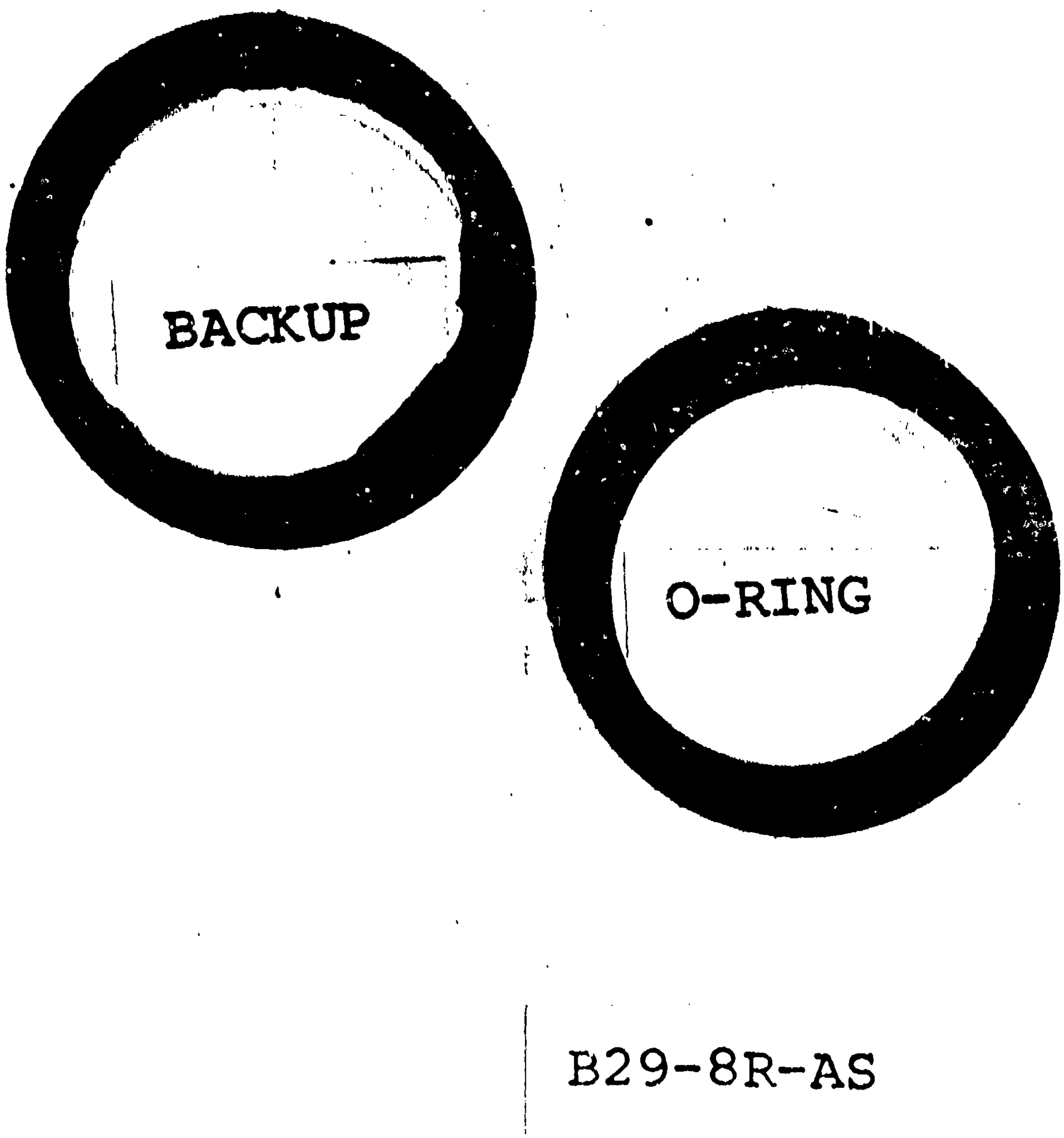


Figure 65. Candidate B29 Backup After Additional Screening Test. O-ring is in good condition.

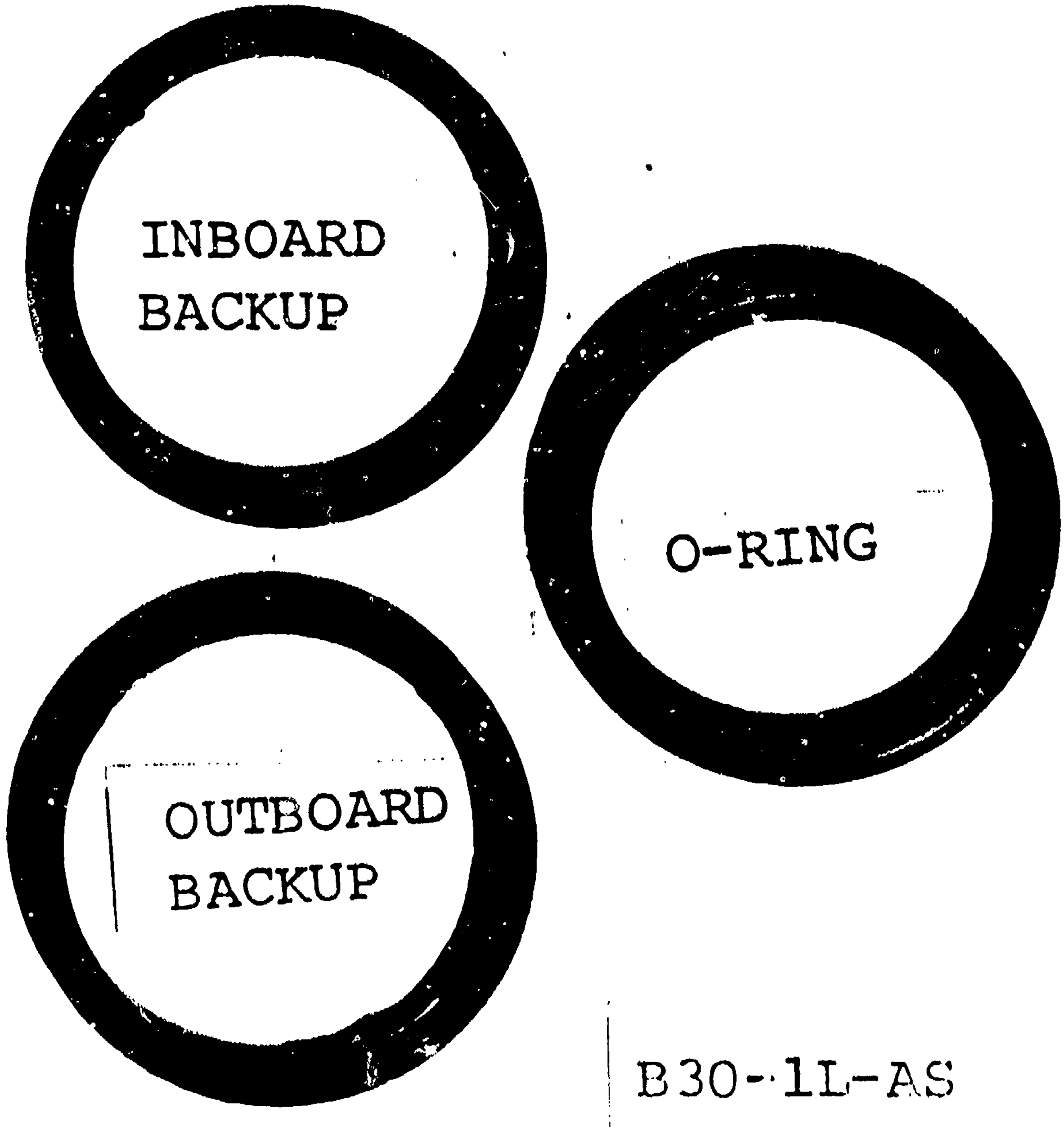


Figure 66. Candidate B30 Backup After Additional Screening Test. O-ring is in excellent condition.

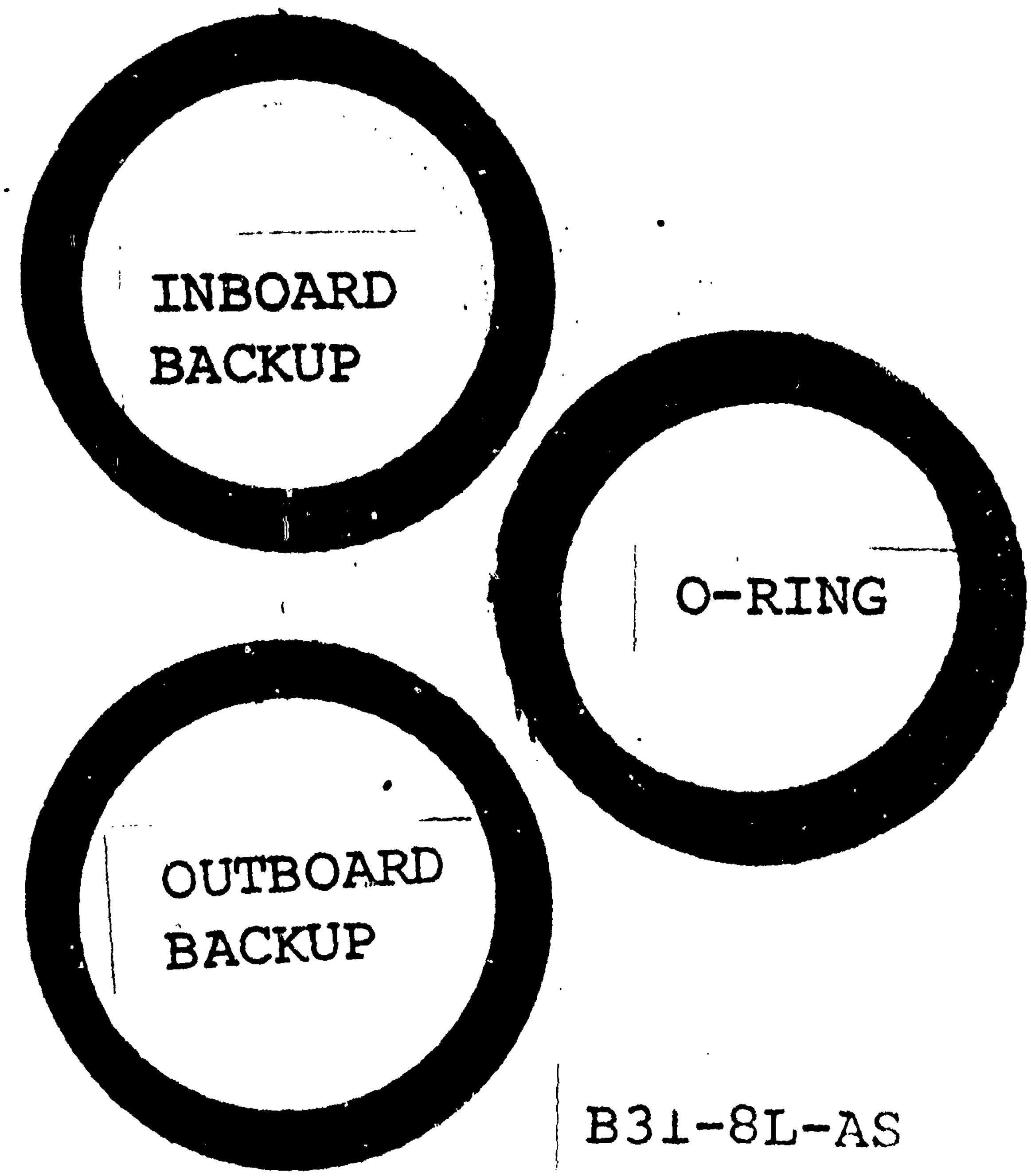


Figure 67. Candidate B31 Backup After Additional Screening Test. Seal finished test but failed due to leakage.

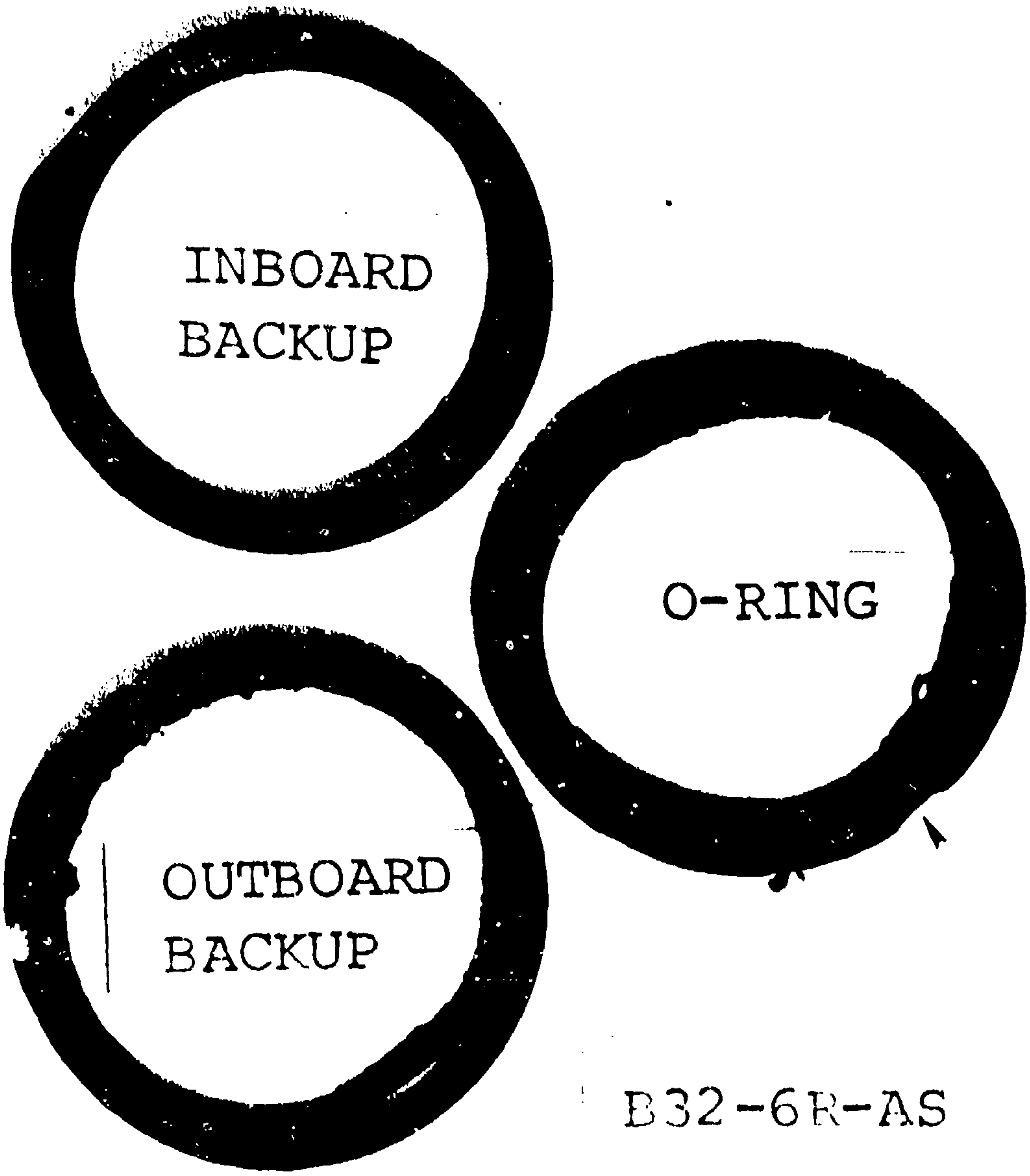


Figure 68. Candidate B32 Backup After Additional Screening Test.
Arrow denotes damage due to scored rod, O-ring has rolled and nibbled.

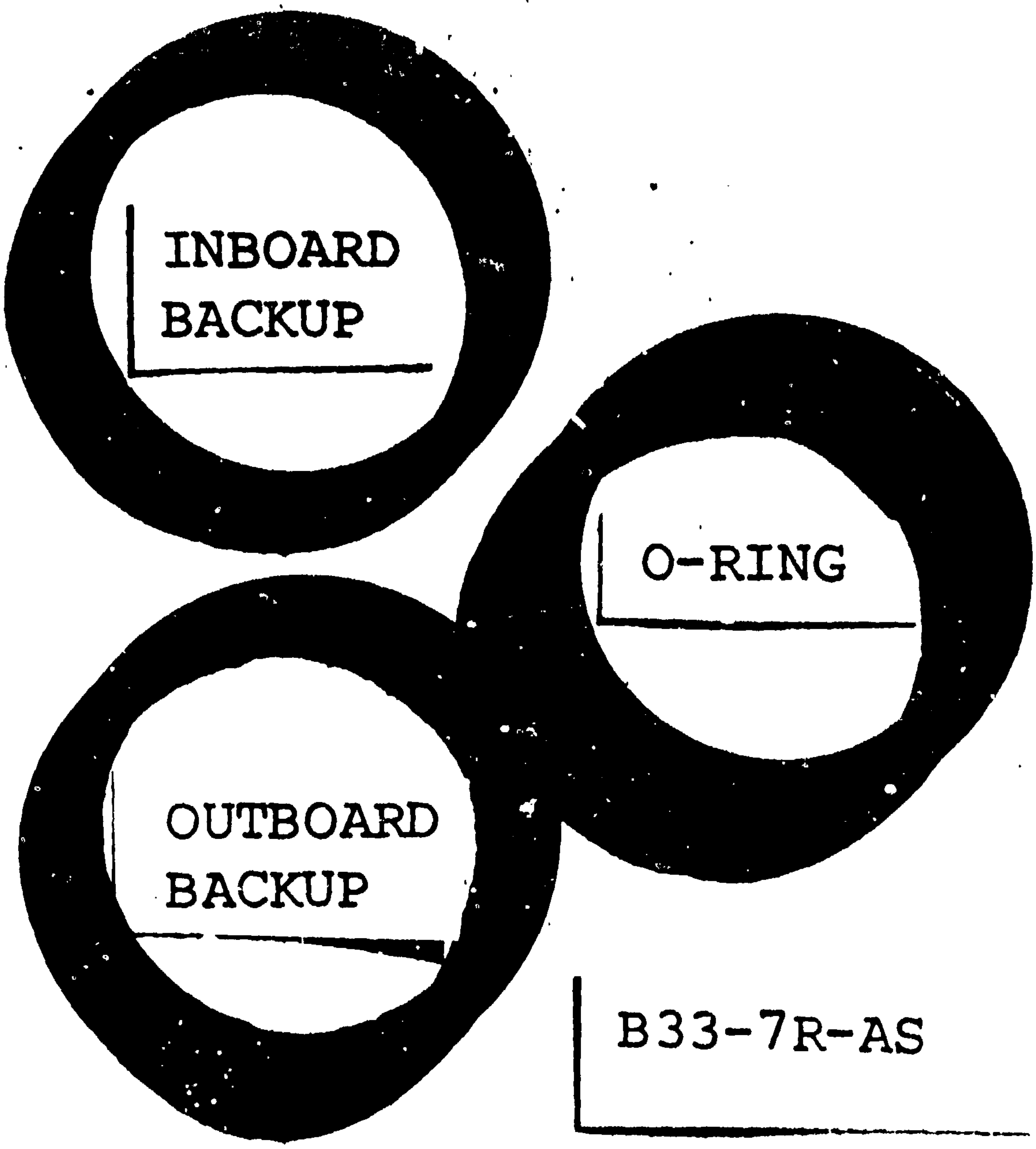


Figure 69. Candidate B33 Backup After Additional Screening test. O-ring is severely nibbled and has rolled.

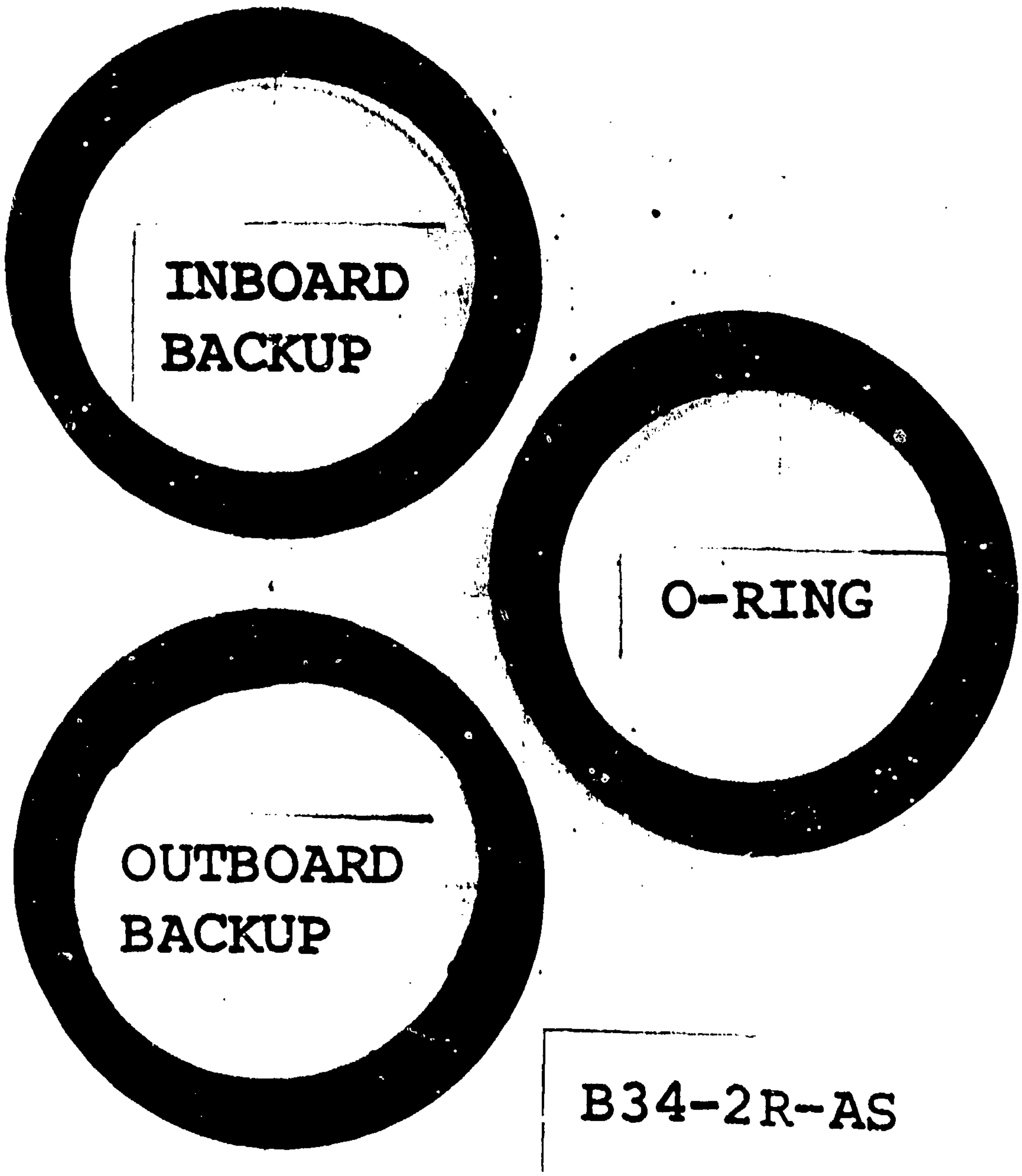


Figure 70. Candidate B34 Backup After Additional Screening Test. O-ring condition is fair. Dynamic leakage was 2 drops in 1.29 x 10^6 endurance cycles.

3.2 Scrapers

A total of 8 configurations were installed in chew tester housings and tested. The scrapers are ranked based upon the total contaminant volume allowed past the scraper and upon wear of the rod due to scraper material or configuration. Ambient temperature was 170° F. during the test. All candidates were subjected to 3.30 x 10^6 endurance cycles for the equivalent of 26801 feet of rod passing under the scraper in the course of completing 24 blocks of the endurance spectrum. The contaminant used was AC Coarse Test Dust.

From these tests, Candidate S7 from Dowty Ltd. of the United Kingdom was selected to be included in the Long Life Test for determination of rod wear with extended cycling.

During the Long Life Test three new and one improved scraper became available and additional screening tests were conducted to determine the effectiveness of these designs. Test conditions were the same as for the initial screening tests except 3.375 x 10^6 endurance cycles were completed. The result was that all of the new and improved scrapers transmitted less contaminant than the MS28776M9 baseline.

Figure 71 shows the relative performance of the scrapers which were part of the first and second scraper screening tests. The figure shows that all of the new or improved scrapers transmitted less contaminant than the average value of the contaminant transmitted by MS28776M9 for the two tests.

The total volume of contaminant which was allowed past each scraper was determined as follows: According to the test plan, the end cap cavity between the scraper and rod seal were flushed with 175 ml of filtered PD680 (Stoddard solvent) approximately every two days of testing. The contaminant level in the PD680 was determined using a HIAC counter.

The contamination in the fluid sample for each candidate was determined on the HIAC counter in the size ranges of 5-10, 10-25, 25-50, and 50-100, microns. It was assumed for rating the performance of the scrapers that the particles were spherical with a diameter computed by averaging the maximum and minimum values representing the range of interest.

Range (Micron)	Average Dia. (Micron)	Volume (inches^3)
5 - 10	7.5	1.34796 x 10^{-11}
10- 25	17.5	1.71241 x 10^{-10}
25- 50	37.5	1.68495 x 10^{-9}
50-100	75.0	1.34796 x 10^{-8}

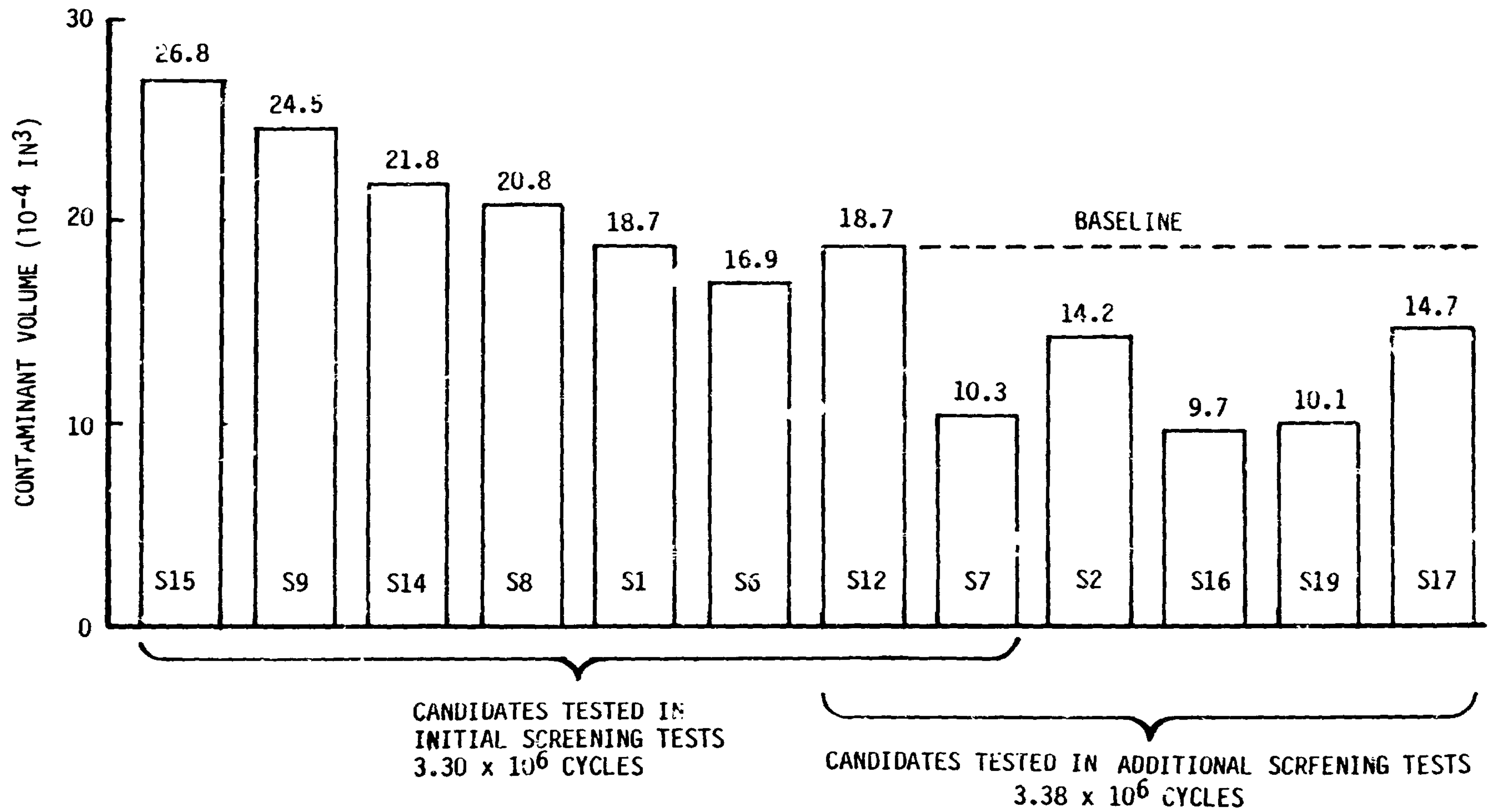


Figure 71. Results of Scraper Screening Tests. The new and improved designs in the additional screening tests performed better than the baseline.

After the particle count was determined for each candidate the total volume of contaminant represented in the sample was calculated using the following formula:

$$V_s = \sum_{n=1}^{4} X_n V_n$$

Where: V_s = total contaminant volume in 175 ml sample
V_n = volume of a particle of nth average diameter
X_n = number of particles of nth average diameter (counted in a 175 ml fluid sample minus the "tare" number of particles in the flushing fluid)
n = 1 average dia = 7.5 micron
2 average dia = 17.5 micron
3 average dia = 37.5 micron
4 average dia = 75.0 micron

A total of ten particle counts was made for each scraper candidate in the initial screening test period. The total contaminant volume of the ten particle counts represents the relative performance of the candidate. In the additional screening tests eleven particle counts were made for each scraper candidate.

Visual examination of the piston rods after the tests indicated the plastic material scrapers left a very light, acceptable burnished rod surface appearance with no appreciable differences among the plastic materials. The two metal scrapers left a moderate, acceptable burnished rod surface which was rougher than that of the plastic material scrapers.

The scrapers were examined after the test. Wear was minimal for all scrapers. Each scraper was evaluated for signs of distortion which may have contributed to transmission of contaminant. At least three candidates exhibited curling of the cleaning lip from the rod.

Table 10 summarizes the scraper screening test results.

An analysis was made to determine if the scraper ID increases enough with temperature increase to eliminate an interference fit with the rod. Three candidates showed the probability of a clearance with the rod at 170° F. which was the minimum ambient air temperature. See paragraph 5.3 for a detailed discussion on thermal expansion of the scraper candidates tested.

The evaluation plan for scrapers originally had included particles up to 200 micron in size because the distribution of particle sizes in the AC standard coarse test dust consisted of 8 percent particles in the 100 to 200 micron range.

TABLE 10. SUMMARY OF SCRAPER SCREENING TEST RESULTS

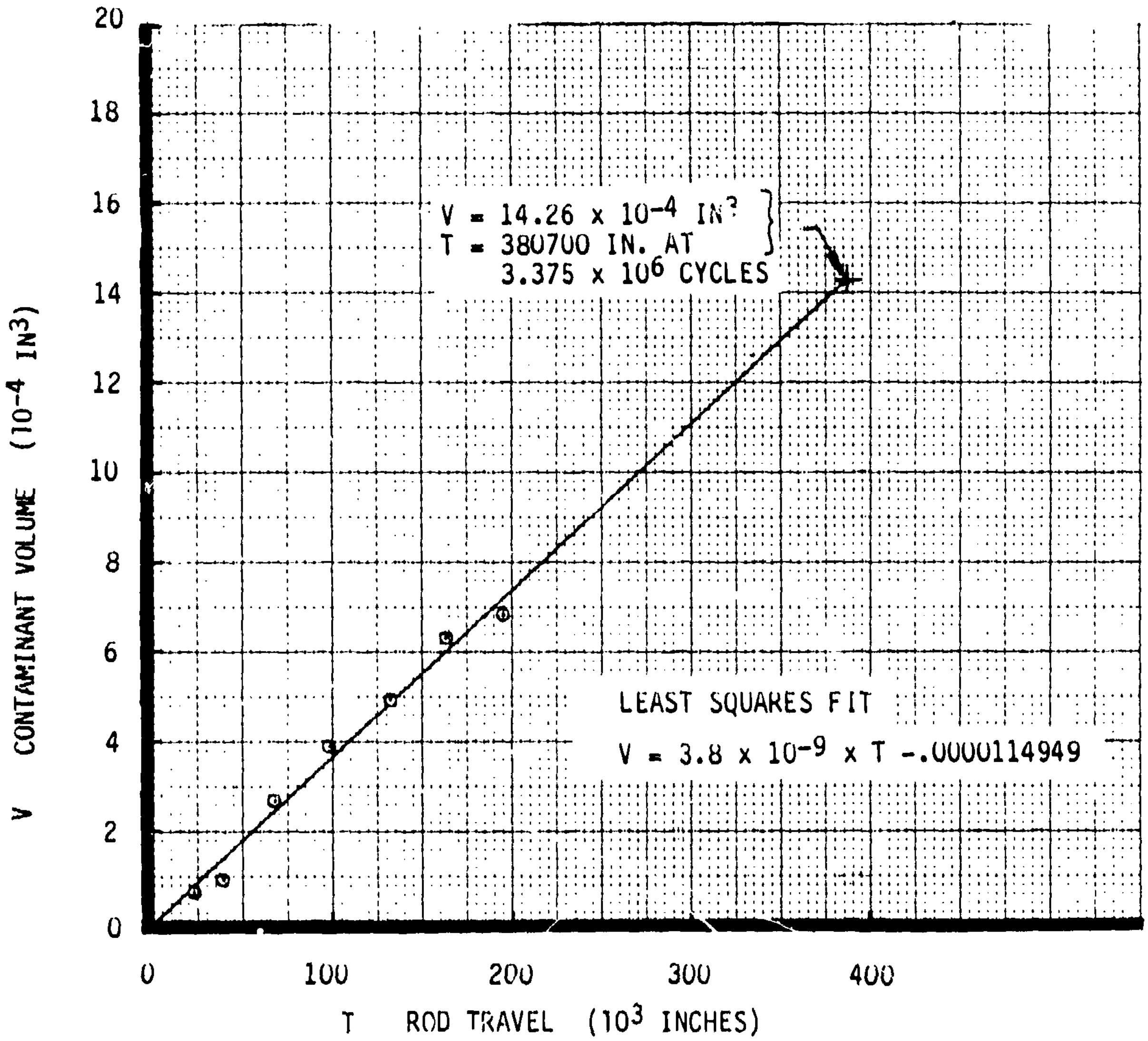
OVERALL RANK	SCRAPER CANDIDATE	INITIAL SCREENING TEST TOTAL CONTAMINANT (10^{-4} IN^3)	ROD COND	MATERIAL	NOTE
7/8*	S12	24.3	MA	Aluminum Bronze	MS28776M9 - Baseline
10	S14	21.8	LA	Polyurethane	Disogrin
9	S8	20.8	LA	Molythane	Parker Packing
6	S6	16.9	MA	Aluminum Bronze	Hercules
12	S15	26.8	LA	Compound Code 14	W. S. Shamban
3	S7	8.1	LA	Acetal Resin Plastic	Dowty, Ltd.
11	S9	24.5	LA	Thermoplastic Rubber	Greene, Tweed
7/8	S1	18.7	LA	TFE	C. E. Conover
		SCREENING TEST OF ADDITIONAL CANDIDATES			
1	S16	9.7	LA	Thermoplastic Rubber	Greene, Tweed
4	S2	14.2	LA	Compound Code 19	W. S. Shamban
3*	S7	12.4	LA	Acetal Resin Plastic	Dowty, Ltd.
2	S19	10.1	LA	Revonoc 18158	C. E. Conover
5	S17	14.7	LA	Proprietary filled TFE	Tetrafluor, Inc
7/8*	S12	13.1	MA	Aluminum bronze	MS28776M9, Baseline

Legend:
LA - Low Wear, Acceptable
MA - Moderate Wear Acceptable

* Overall ranking is based upon average total contaminant for the two tests.

It was discovered during the additional screening tests that O-ring and backup ring pieces from the rod seals adjacent to the scrapers were affecting the accuracy of the particle counter. A standard sieve system was used to remove particles greater than 100 microns absolute to allow use of the particle counter. Consequently, all data is based upon particle counts of contaminant up to 100 microns in size.

The data shown for candidate S2 is a linear regression, least squares fit of data obtained for seven fluid samples on which particle counts were made. In the course of the additional screening tests, a misalignment of parts in the chew tester used for candidate S2 resulted in a scored piston rod three times. Despite efforts to eliminate the problem each time, the scoring caused a deflection of replacement rods and consequently, testing was terminated on candidate S2 after the seventh particle count. Figure 72 shows a plot of the data obtained and the least squares fit. The correlation coefficient for the fit was .9908 which is very good.



DATA

T - INCHES	V - IN^3
22300	$.66 \times 10^{-4}$
39889	$.95 \times 10^{-4}$
66800	2.70×10^{-4}
98921	3.89×10^{-4}
132145	4.96×10^{-4}
163529	6.36×10^{-4}
195334	6.81×10^{-4}

Figure 72. Extrapolation of Contaminant Volume for Candidate Scraper S2

Candidate descriptions after screening test:

Candidate S1; CEC 401-214-011, C. E. Conover

MATERIAL: Revonoc 18156 (C. E. Conover)

CHARACTERISTICS: O-ring sealed; one piece gland.

CONFIGURATION: See Figure 73.

RESULTS: See Figure 85. Minimal wear to scraper. Very light acceptable rod burnishing. Tied for seventh place in contamination exclusion. The temperature expansion analysis indicated a possible diametral clearance at 170° F. Examination of the scraper indicated the lip had curled away from the rod. Scraping action was occurring under the O-ring. Easily installed in a special one piece gland.

Candidate S6; S-34-20, Hercules:

MATERIAL: Bronze

CHARACTERISTICS: Elastomer sealed; metal cone, one piece gland.

CONFIGURATION: See Figure 74.

RESULTS: See Figure 86. Minimal wear to scraper. Moderate acceptable rod wear. Ranked second in contamination exclusion. The temperature expansion analysis indicated this scraper to have an interference fit at 170° F. The scraper maintained its configuration during the test. Easily installed in one piece gland.

Candidate S7; 120-218-1709, Dowty Ltd:

MATERIAL: Acetal plastic

CHARACTERISTICS: O-ring sealed, "snap in" assembly, one piece gland.

CONFIGURATION: See Figure 75.

RESULTS: See Figure 87. Minimal wear to material. Very light acceptable rod burnishing. Ranked third in contamination exclusion. The temperature expansion analysis indicated an interference fit at 170° F. The scraper maintained its configuration during the test. The 1 inch diameter rod size is the smallest size which should be attempted with a one piece gland.

Candidate S8; 18701000-312, Parker Packing

MATERIAL: Molythane (Parker), polyurethane with M_oS_2

CHARACTERISTICS: O-ring energized, two piece gland.

CONFIGURATION: See Figure 76.

RESULTS: See Figure 88. Very light acceptable rod burnishing. Minimal wear to scraper material. Ranked ninth in contamination exclusion. The temperature expansion analysis indicated an interference fit at 170° F. The scraper appeared to roll slightly in the groove so that the shoulder (inboard) was touching the rod in addition to the O-ring loaded lip. A two piece gland is recommended for installation.

Candidate S9; 5994-214-959, Greene, Tweed

MATERIAL: Hytrel thermoplastic rubber

CHARACTERISTICS: Spring energized; two-piece gland

CONFIGURATION: See Figure 77.

RESULTS: See Figure 89. Very light acceptable rod burnishing. Minimal wear to scraper material. Ranked eleventh in contamination exclusion. The temperature expansion analysis indicated a possible diametral clearance at 170° F. A two piece gland is required.

Candidate S12; MS28776M9

MATERIAL: Bronze

CHARACTERISTICS: All metal, no sealing

CONFIGURATION: See Figure 78.

RESULTS: See Figure 90. Minimal wear to scraper. Moderate acceptable rod wear. Tied for seventh place in exclusion of contamination. The temperature expansion analysis indicated an interference fit at 170° F.

Candidate S14; 006015-000A, Disogrin

MATERIAL: Polyurethane

CHARACTERISTICS: One piece groove "snap-in" design

CONFIGURATION: See Figure 79.

RESULTS: See Figure 91. Very light acceptable rod burnishing. Minimal wear to scraper material. Ranked tenth in contamination exclusion. The scraper appears to have maintained its shape during the test. The temperature analysis indicates an interference fit at 170° F. Easy to install in one piece gland.

Candidate S15; S30395-9G-14, W. S. Shamban

MATERIAL: Glass/Moly filled TFE

CHARACTERISTICS: O-ring sealed, one piece gland

CONFIGURATION: See Figure 80.

RESULTS: See Figure 92. Very light acceptable rod burnishing. Minimal wear to scraper material. Ranked twelfth in contamination exclusion. Wear pattern on the inner diameter of the scraper indicated the cleaning lip had curled away from the rod; contact was at the inner shoulder of the scraper. Temperature analysis indicated an interference fit with the rod. Moderate effort to install in one piece gland.

Candidate Descriptions After Additional Screening Tests

Candidate S2; S32925-9P-19, W. S. Shamban

MATERIAL: Shamban Compound Code 19.

CHARACTERISTICS: O-ring sealed, contacts rod at both sides of scraper.

CONFIGURATION: See Figure 81.

RESULTS: See Figure 93. Total contaminant passed was 6.8 x 10^{-4} cubic inches thru 1.76 x 10^6 cycles. A least squares fit of this data allows extrapolation of data to 3.375 x 10^6 cycles. Volume of contaminant is 14.2 x 10^{-4} in^3 by extrapolation. This assembly suffered three scored rods not related to the candidate in test and was finally removed from test after repeated efforts to eliminate the scoring had failed. Ranked fourth overall in contamination exclusion.

Candidate S7; 120-218-1709, Dowty Ltd. (Best performance in initial screening tests)

MATERIAL: Acetal plastic

CHARACTERISTICS: O-ring sealed, "snap in" assembly, one piece gland.

CONFIGURATION: See Figure 75. Same as tested in the initial scraper screening tests.

RESULTS: See Figure 94. The ID was tight on a .998 inch diameter plug. The rod surface finish had light wear with the appearance of polished off high places in the grind marks. The scraper has a uniform wear pattern around the ID of the lip. Ranked third overall in contamination exclusion.

Candidate S12; MS28776M9 (Baseline)

MATERIAL: Bronze

CHARACTERISTICS: All metal, no sealing

CONFIGURATION: See Figure 78. Same as in Initial Screening Tests

RESULTS: See Figure 95. The inner diameter had worn to greater than .998 from a new dimension of .9903. The piston rod finish has a dull frosted appearance on the area contacted by the scraper. Thermal expansion analysis of the new scraper shows an interference fit at 170°F. Tied for seventh place overall in contamination exclusion.

Candidate S16; 3534-00998-0122-0235, Greene, Tweed

MATERIAL: Hytrel thermoplastic rubber

CHARACTERISTICS: Fits one backup width MIL-G-5514 gland for -214 O-ring, O-ring energized.

CONFIGURATION: See Figure 82.

RESULTS: See Figure 96. The lip is not worn and appears to have remained in contact with the rod. The scraper had to be cut in order to remove it. Very little contaminant had accumulated within the end cap. Rod wear is very light. Scraper is ranked first overall in contamination exclusion. At 170°F, the scraper had an interference fit with the rod before testing.

Candidate S17; TF1027-7214A, Tetrafluor, Inc.

MATERIAL: Proprietary Filled TFE

CHARACTERISTICS: O-ring sealed, single wiping edge, fits same groove as candidate S2.

CONFIGURATION: See Figure 83.

RESULTS: See Figure 97. Scraper is ranked fifth overall in contamination exclusion. The scraper was a tight fit on the .998 dia rod. The rod has light wear with a few axial wear marks as deep as the original 13 RMS finish. The scraper was damaged when being removed. An extrusion ridge around both the inboard and outboard edges of the ID indicate the possibility of overfill of the groove. The wear pattern on the ID indicates that the outer lip had curled away from the rod. The scraper had an interference fit with the rod at 170°F before testing.

Candidate S19; CEC 5091-998-55, C. E. Conover:

MATERIAL: Revonoc 18158

CHARACTERISTICS: Molded elastomer seal, fits same groove as candidate S2.

CONFIGURATION: See Figure 84.

RESULTS: See Figure 98. The wear pattern on the ID of the scraper indicated uniform contact around the rod. The rod has a slight discoloration and has a light wear pattern on one side indicating some side loading of rod into end cap. Normally, Revonoc 18158 material is not abrasive. Ranked second overall in contamination exclusion.

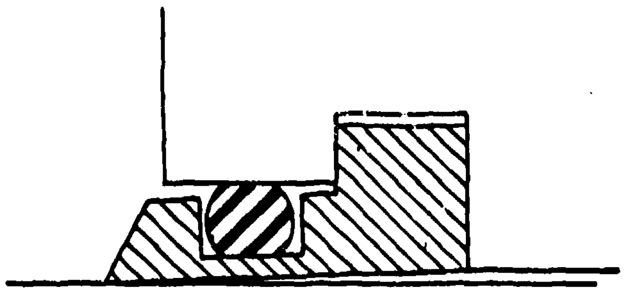


Figure 73. Candidate S1; CEC 401-214-011; C. E. Conover

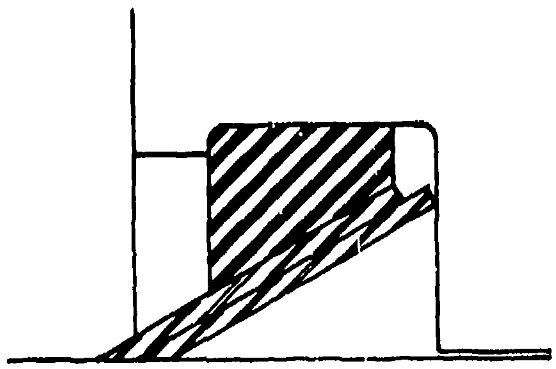


Figure 74. Candidate S6; S-34-20; Hercules

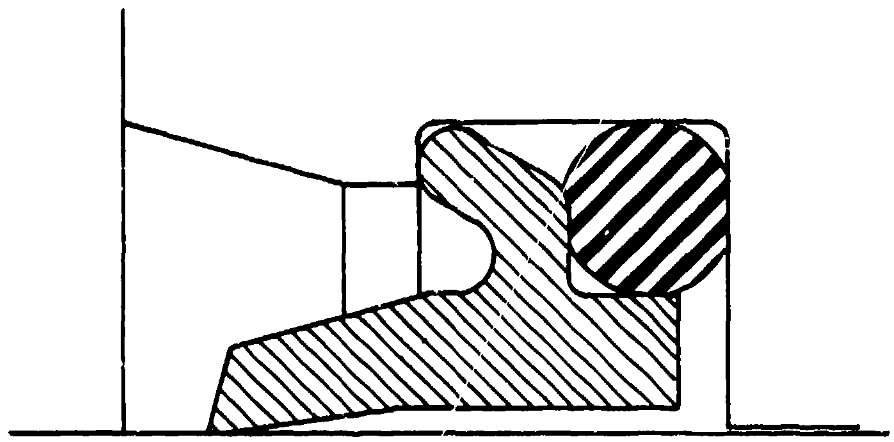


Figure 75. Candidate S7; 120-218-1709; Dowty, Ltd.

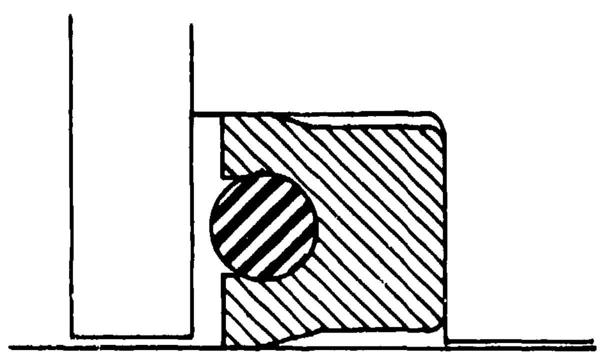


Figure 76. Candidate S8; 18701000-312; Parker Packing

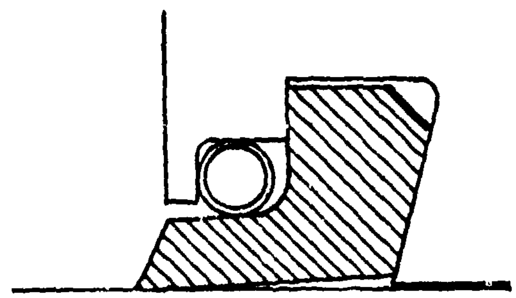


Figure 77. Candidate S9; 5994-214-959; Greene, Tweed

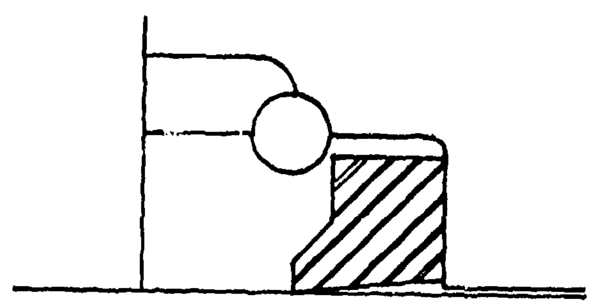


Figure 78. Candidate S12; MS28776M9

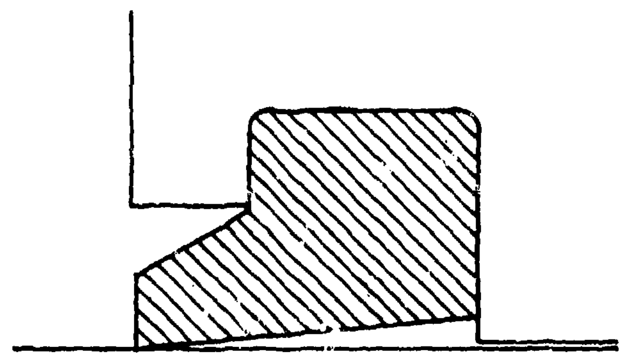


Figure 79. Candidate S14; 006015-000A; Disogrin

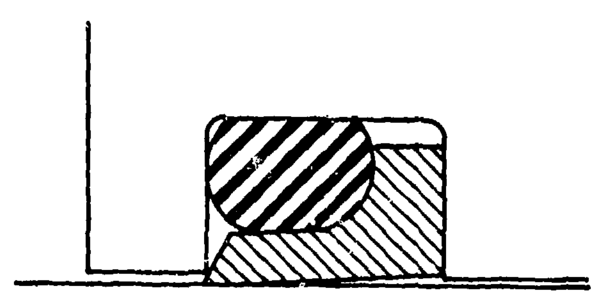


Figure 80. Candidate S15; S30395-9G-14; W. S. Shamban

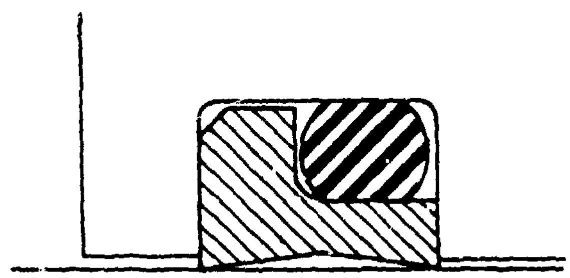


Figure 81. Candidate S2; S32925-9P-19; W. S. Shamban

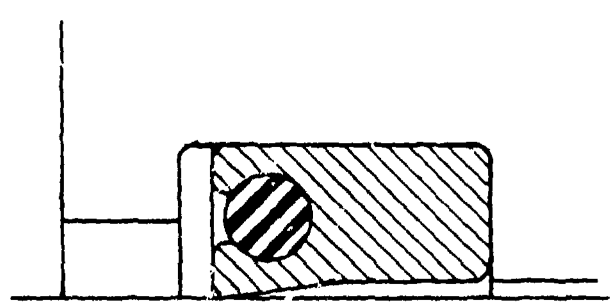


Figure 82. Candidate S16; 3534-00998-0122-0235; Greene, Tweed

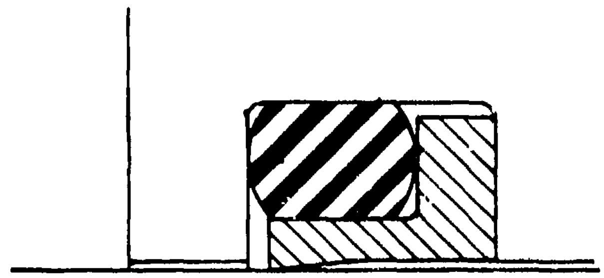


Figure 83. Candidate S17; TF1027-7214A; Tetrafluor, Inc.

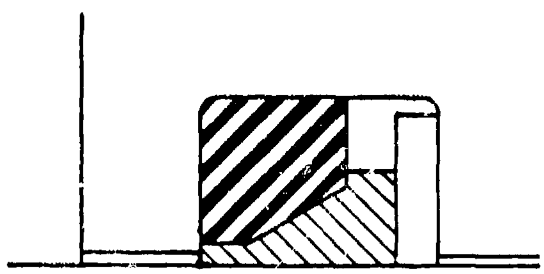


Figure 84. Candidate S19; CEC 5091-998-55; C. E. Conover

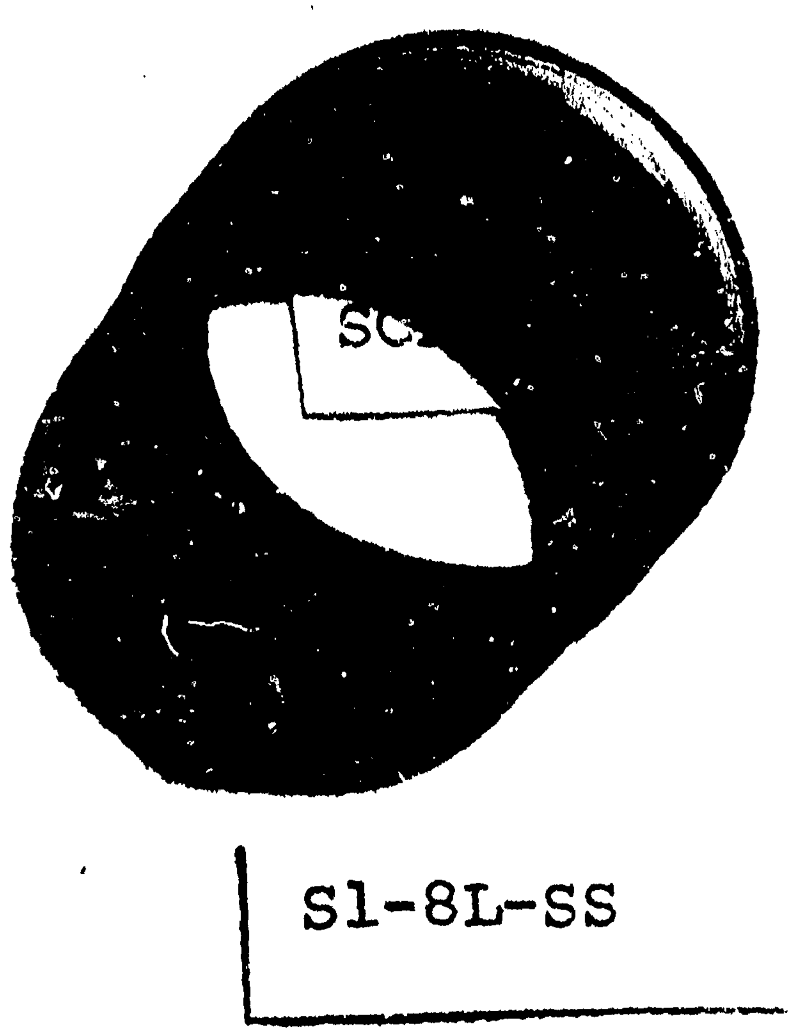


Figure 85. Candidate S1 After Scraper Screening Test.

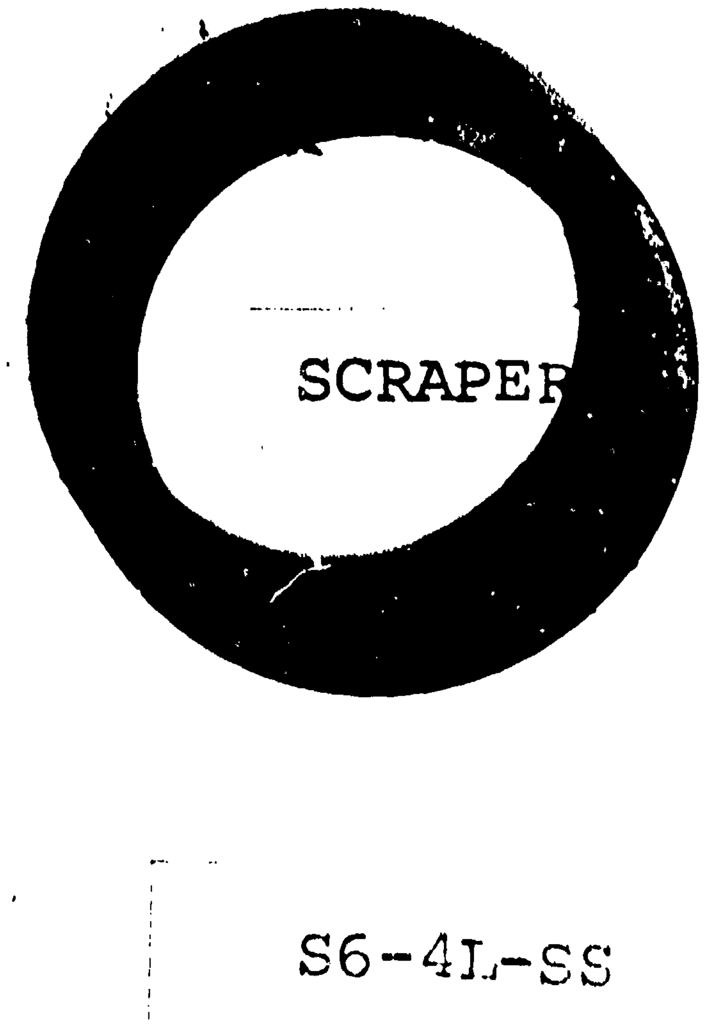


Figure 86. Candidate S6 After Scraper Screening Test.
Bronze cones with elastomer seal.

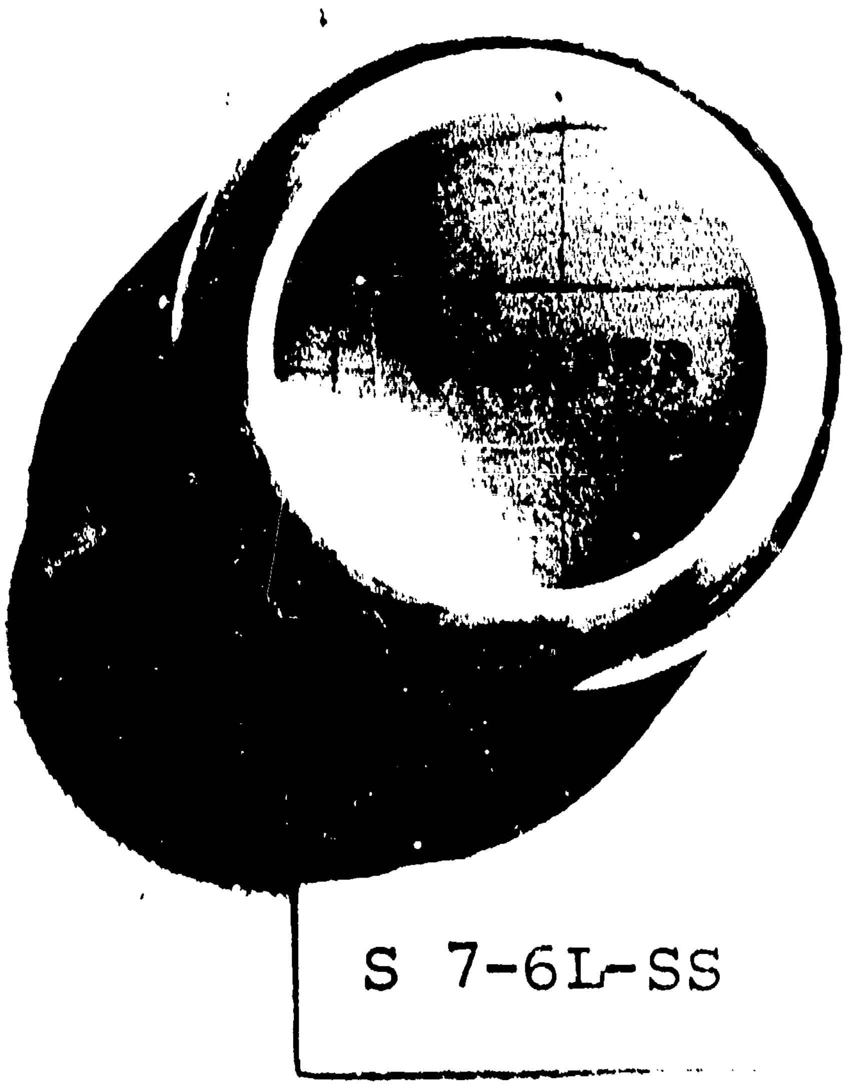


Figure 87. Candidate S7 After Scraper Screening Test. Acetal resin material scraper.

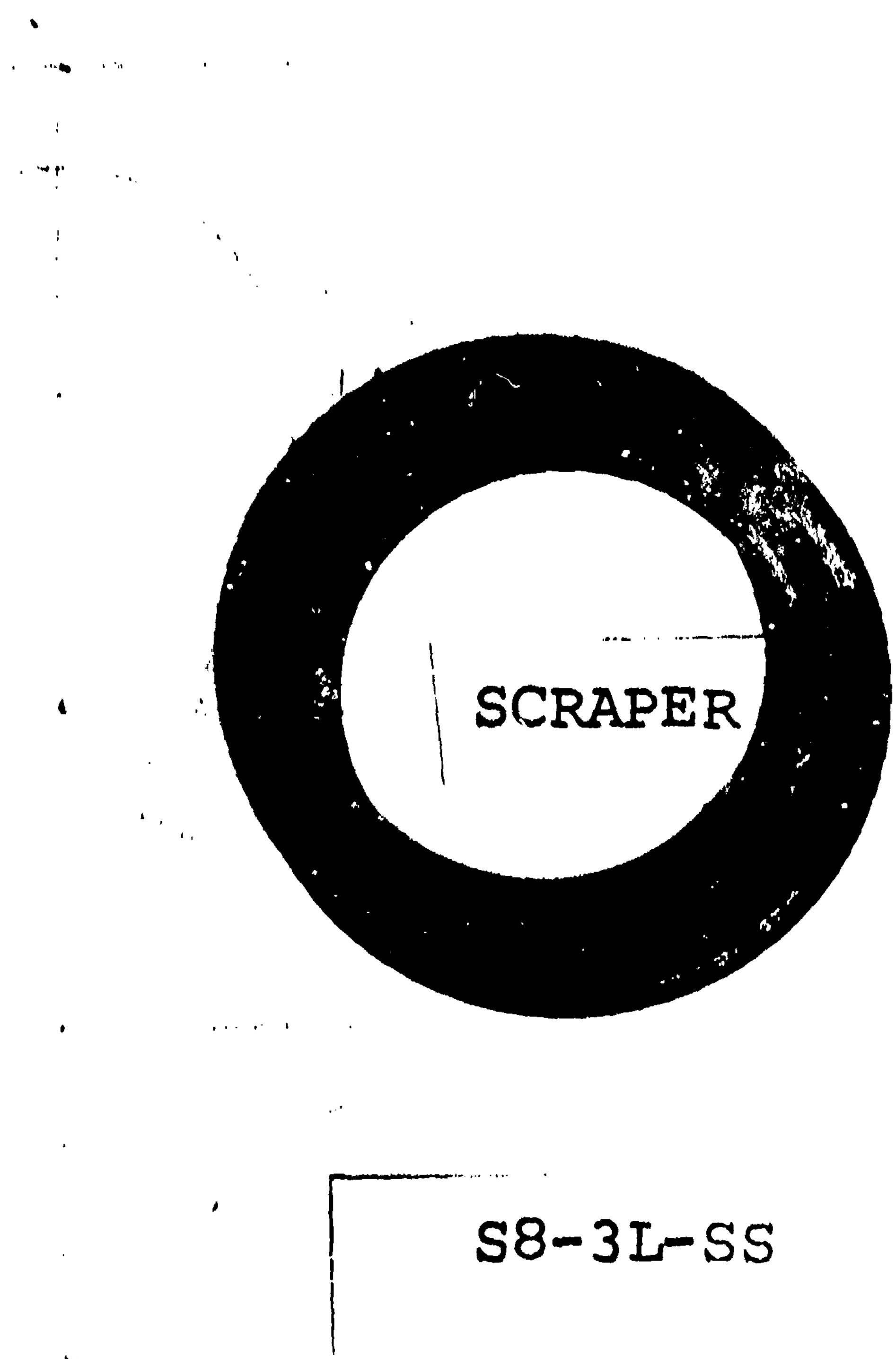


Figure 88. Candidate S8 After Scraper Screening Test.
Molythane material with nitrile O-ring energizer.

Figure 89. Candidate S9 After Scraper Screening Test.
Hytrel material with spring energizer.

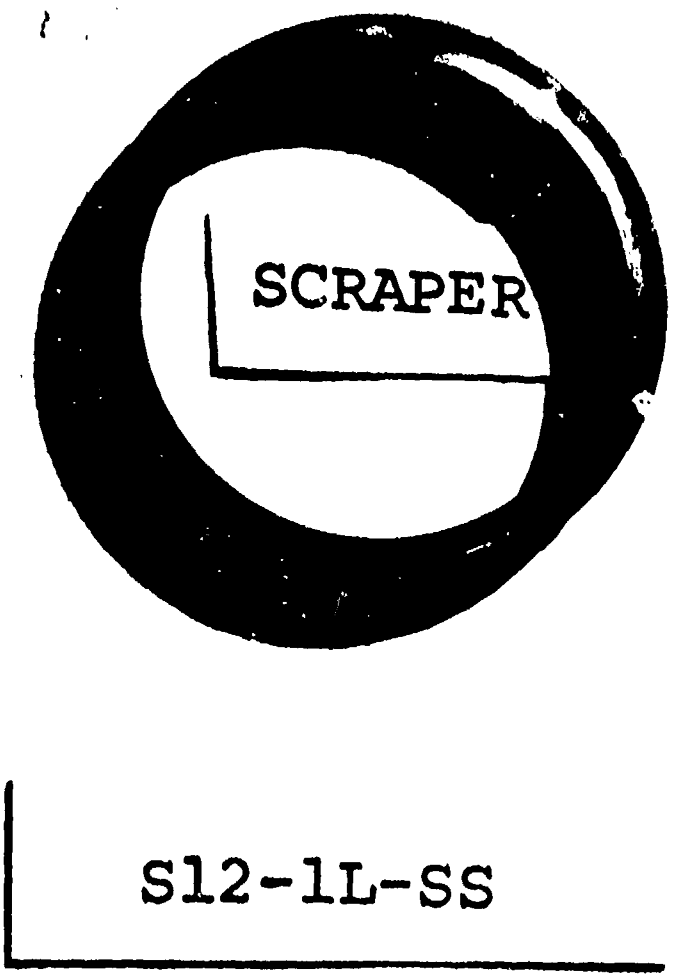


Figure 90. Candidate S12 After Scraper Screening Test.
Baseline MS28776M9 scraper of bronze material.

Figure 91. Candidate S14 After Scraper Screening Test. Polurethane material is NFPA configuration.

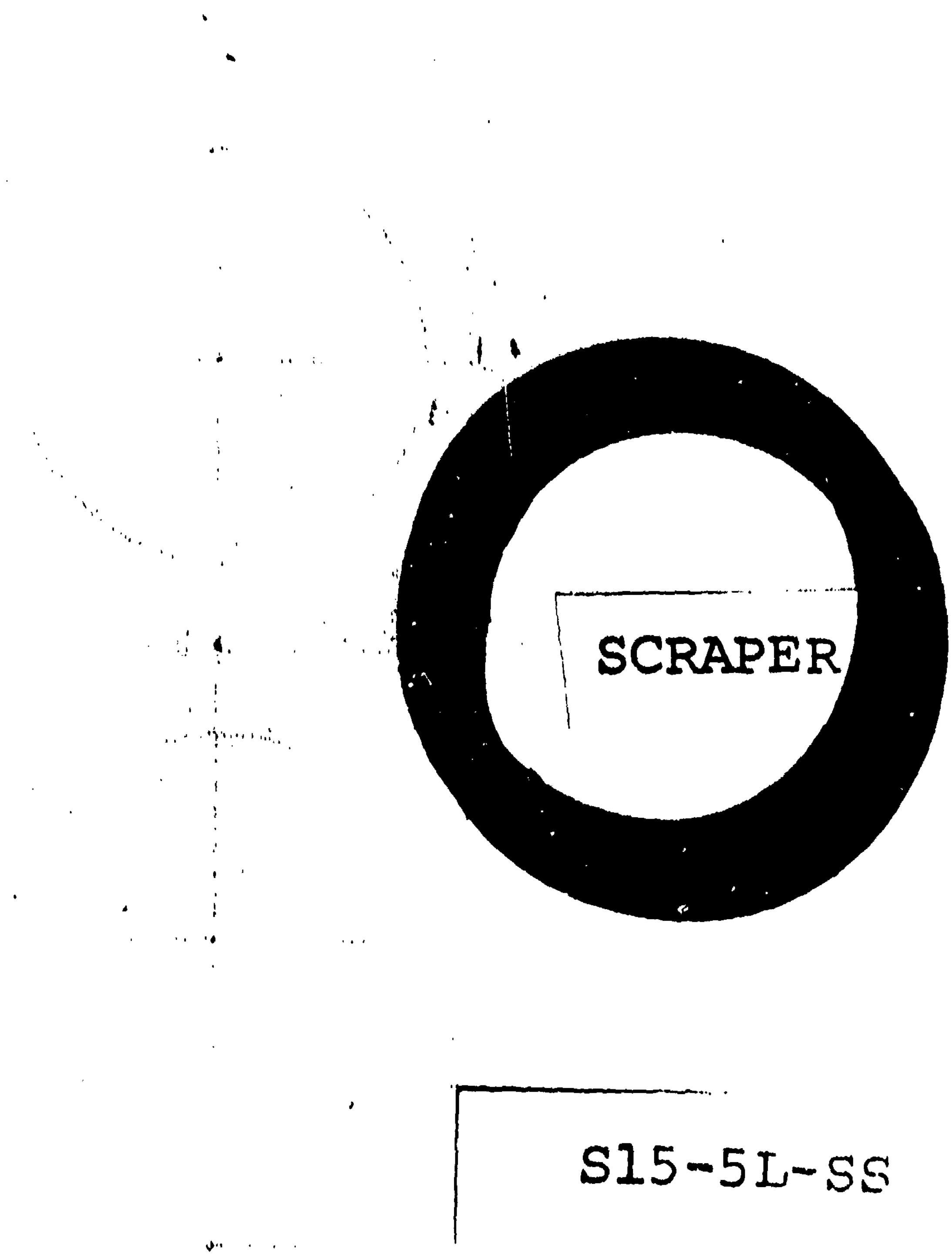


Figure 92. Candidate S15 After Scraper Screening Test.
Damage occurred during removal after test.

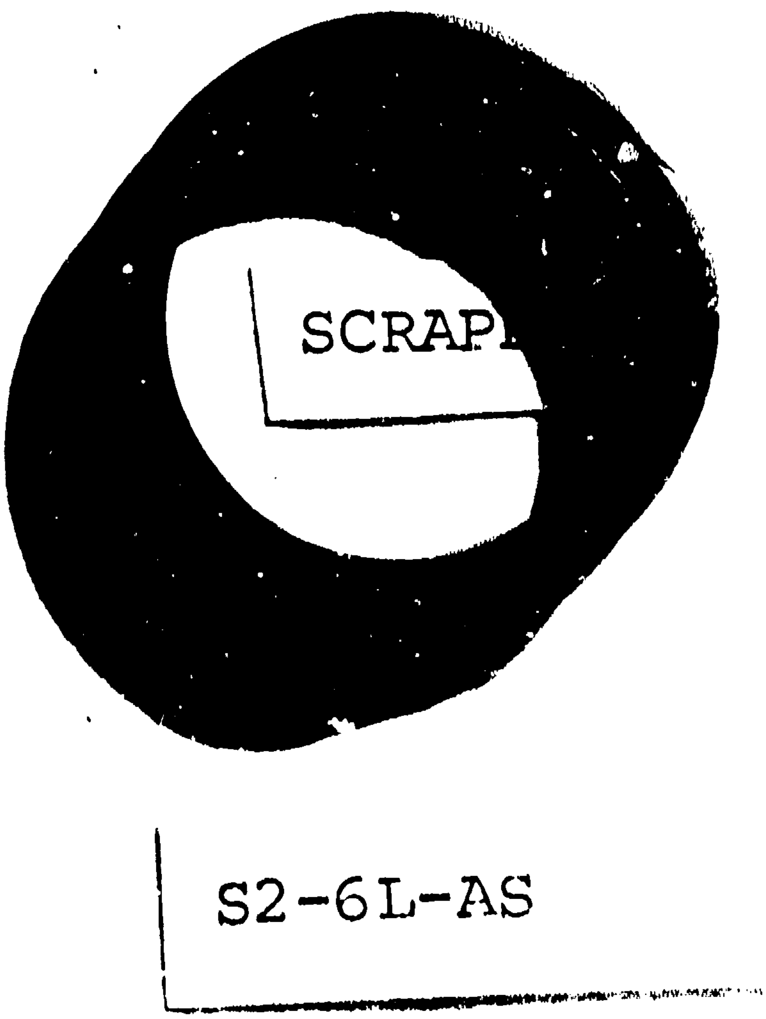


Figure 93. Candidate S2 Scraper After Additional Screening Test.

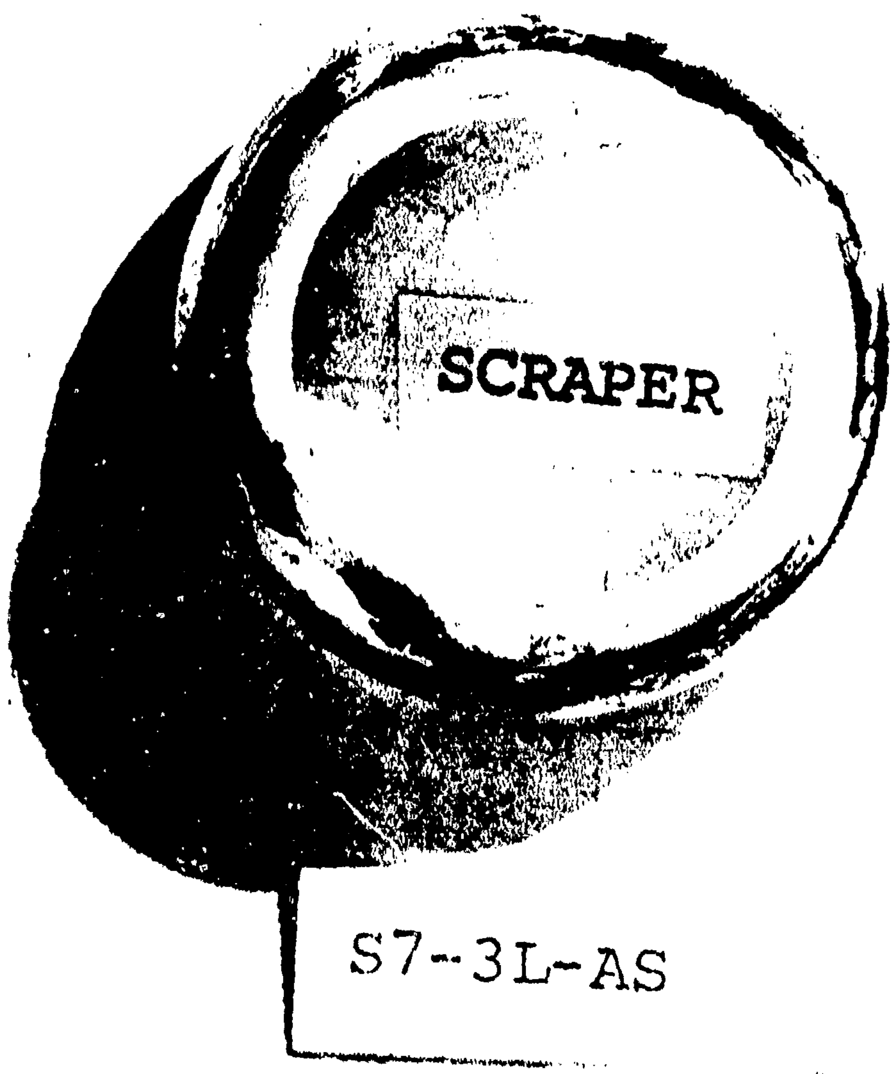


Figure 94. Candidate S7 Scraper After Additional Screening Tests. Damage to OD occurred during removal after test.

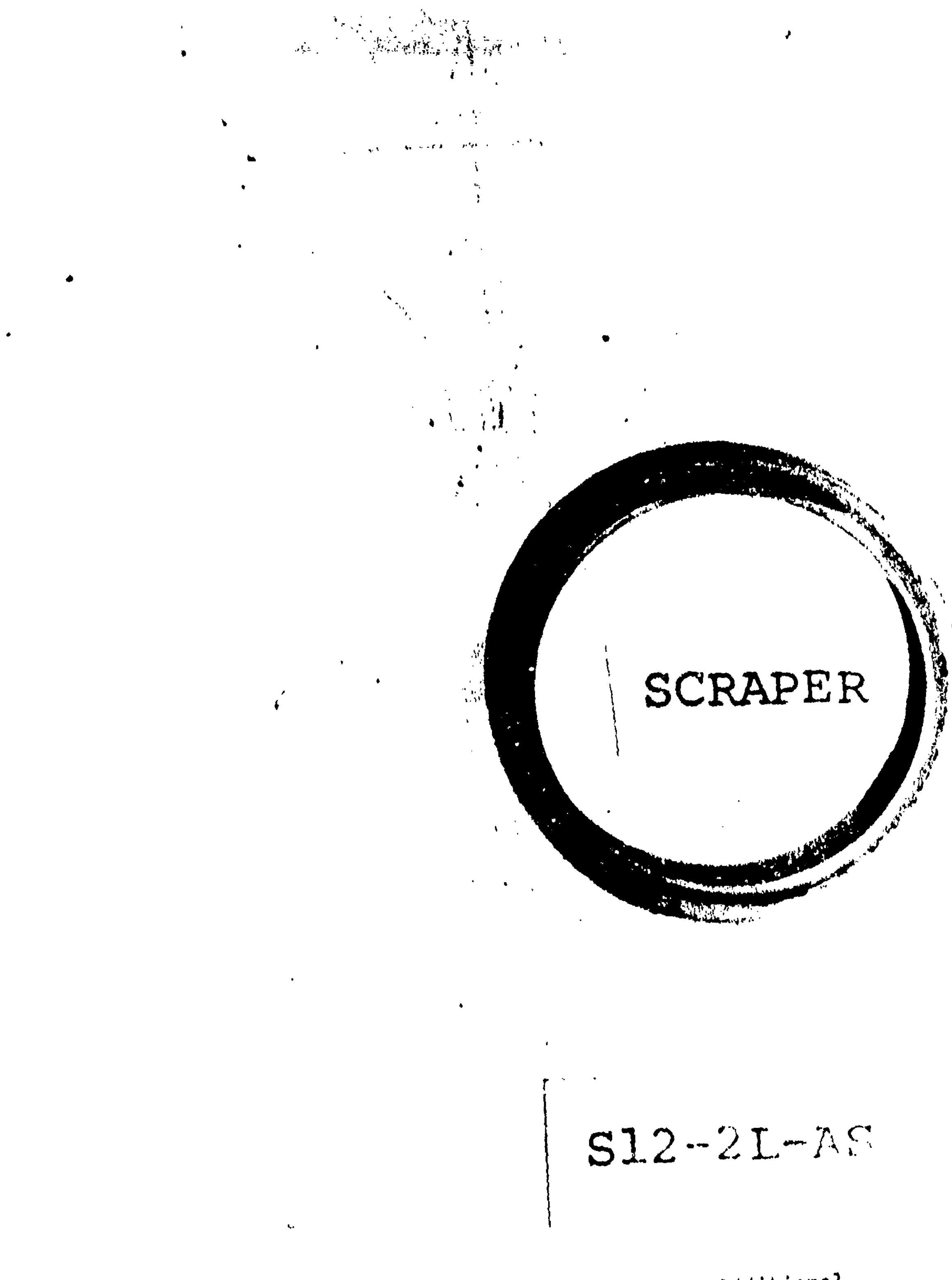


Figure 95. Candidate S12 Scraper After Additional Screening Tests. MS28776M9 was baseline for all scraper tests.

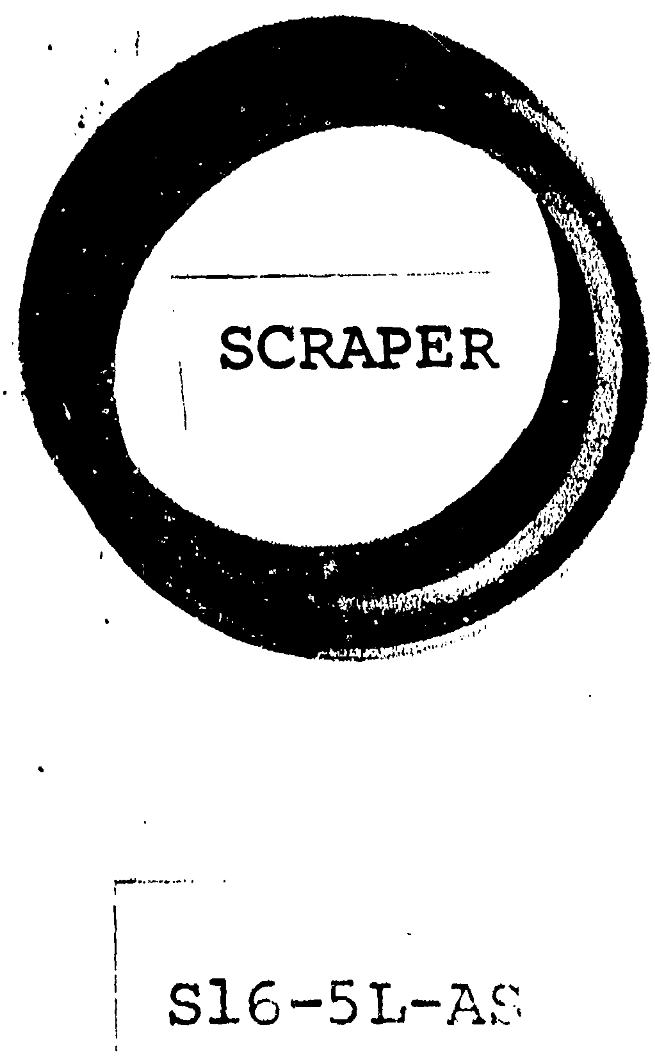


Figure 96. Candidate S16 Scraper After Additional Screening Test.

Figure 97. Candidate S17 Scraper After Additional Screening Test.

Figure 98. Candidate S19 Scraper After Additional Screening Test.

3.3 Single Stage Rod Seals

A total of 11 configurations were tested. Unless noted, all candidates completed 20 blocks totaling 3.44 x 10^6 endurance cycles. Oil temperature was 220 to 250°F for the endurance cycles. Every five days a -65°F static leakage test was conducted. The candidates were tested in torsion bar loaded hydraulic cylinders to simulate air loads.

Table 11 Summarizes performance of all single stage rod seal candidates tested. Leakage was the most significant difference between candidates. The elastomer seals leaked less than the plastic seals. Results were as follows:

Candidate RS 3 (7214FT-972-4780)

MATERIAL: Greene,Tweed Fluoromer compound seal, nylon outboard backups, unfilled TFE inboard backups.

CHARACTERISTICS: Elastomeric T-Seal with two stage nylon and TFE backup.

CONFIGURATION: See Figure 99.

RESULTS: See Figure 110. The seal and backups were in good condition. Leakage was zero for static, low temperature, and dynamic conditions. The rod exhibited a moderate wear pattern underneath the nylon backups around the circumference of the rod.

Candidate RS 7 (S33050-214P-18)

MATERIAL: MIL-P-83461 elastomer, mineral filled TFE, W. S.Shamban, material code 18.

CHARACTERISTICS: "L" shaped two piece backup with elastomer lip seal.

CONFIGURATION: See Figure 100.

RESULTS: See Figure 111. The elastomer and backup were not worn. The rod exhibited light wear. Leakage was zero for static, low temperature, and dynamic conditions.

TABLE 11. SUMMARY OF SINGLE STAGE ROD SEAL SCREENING TESTS

ASSEMBLY NO.	CANDIDATE NO.	TOTAL STATIC LEAKAGE	TOTAL -65°F LEAKAGE	TOTAL DYNAMIC LEAKAGE	SEAL CONDITION	ROD CONDITION	SEAL TYPE
1	RS24	0	0	.4 cc	Good	Good	P
2	RS25	2d	2d	5.5 cc	Good	Low Wear	P
3	RS26	1d	2d	2.2 cc	Good	Good	P
4	RS27	0* *until point of failure	0*	FAILURE	Seal extruded due to backup wear at 2.89 x 10^6 cycle	Good	E
	RS22	0	0	0	Good, completed 209222 cycles	Good	P
5	RS13	1d	1d	1d	Good	Very low wear	E
6	RS28	0	0	79.66 cc	Small scratches on ID. Removed at 686387 cycles	--- ---	P
	RS28	81.05cc	7.5 cc	70 cc	Shallow scratches on ID. Removed after 1.78 x 10^6 cycles	Moderate wear due to nylon backup	P
7	RS3	0	0	0	Good	Moderate wear due to nylon backup.	E
8	RS29	0	0	0	Good - small fatigue crack around ID next to backup	Very low wear.	E
9	RS7	0	0	0	Good	Low wear	E
10	RS20	0	0	0	Backup good; moderate nibbling of Elastomer on ID	Good	E

P = plastic E = elastomer

Candidate RS 13 (501-016-1109-01)

MATERIALS: Dowty 1109 nitrile seal, unfilled TFE backup.

CHARACTERISTICS: Rectangular elastomeric seal with integral backup.

CONFIGURATION: See Figure 101.

RESULTS: See Figure 112. The seal and backup were in good condition. The backup exhibited some wear. Leakage was 1 drop static, 1 drop during low temperature, and 1 drop dynamic. The rod had very light wear in the area in contact with the seal.

Candidate RS 20 (CEC5056-214)

MATERIAL: MIL-P-83461 elastomer, Revonoc 18158 backup with interference fit on rod.

CHARACTERISTICS: Trapezoid shaped elastomer with thick cross section trapezoid shaped backup.

CONFIGURATION: See Figure 102.

RESULTS: See Figure 113. The elastomer had moderate nibbling around the circumference of the I.D. adjacent to the backup. Backup condition was good. Leakage was zero for static, low temperature, and dynamic conditions. No rod wear occurred.

Candidate RS 22 (TF831M-7214 seal, M83461/1-318 O-ring)

MATERIAL: Tetralon 720 seal.

CHARACTERISTICS: Determine if 3/16" cross section O-ring energizer provides improved performance of cap seal compared to 1/8" cross section O-ring energized cap seal.

CONFIGURATION: See Figure 103.

RESULTS: See Figure 114. This candidate was installed upon failure of RS27 and had accumulated only 209222 cycles by the last day of testing. Seal condition was good. Leakage was zero for all three test conditions. No rod wear occurred.

Candidate RS24 (TF831-214-1 Seal, TF95-214 Backup (2), M83461/1-214 O-Ring

MATERIAL: Tetralon 720, Tetrafluor

CHARACTERISTICS: No backup width cap seal with two stage backups

CONFIGURATION: See Figure 104.

RESULTS: See Figure 115. Seal and backups are in good condition. Static leakage was 0 drops. Low temperature leakage was 0 drops. Dynamic leakage was 0.4 cc. The rod was in good condition in the area contacted by the seal.

Candidate RS25 (S30650-214-14, Seal, S33012-214-14 backup (2), M83461/1-214 O-Ring

MATERIAL: W. S. Shamban, Compound Code 14.

CHARACTERISTICS: No backup width cap seal with two stage backup.

CONFIGURATION: See Figure 105.

RESULTS: See Figure 116. Seal and backups are in good condition. Static leakage was 2 drops. Low temperature leakage was 2 drops. Dynamic leakage was 5.5 cc. The rod exhibited light wear under the seal in the area contacted during 1, 2 and 10 percent stroke cycling.

Candidate RS 26 (CEC5058-214 seal, CEC5057-214 backup (2), M83461/1-214 O-ring)

MATERIAL: Revonoc 6200 seal, Revonoc 18158 backups.

CHARACTERISTICS: No backup width cap seal with two stage backup.

CONFIGURATION: See Figure 106.

RESULTS: See Figure 117. Seal and backups were in good condition. The outboard backup exhibited some loss of cross section due to extrusion. Static leakage was 1 drop. Low temperature leakage was 2 drops. Dynamic leakage was 2.2 cc. No rod wear occurred due to seal or backups.

Candidate RS 27 (18701000 Special Std.)

MATERIAL: Parker Z4653 nitrile seal, nitrile O-ring, unfilled TFE backup.

CHARACTERISTICS: O-ring energized 3/16 inch cross section elastomeric lip seal, with integral TFE backup.

CONFIGURATION: See Figure 107.

RESULTS: See Figure 118. On the 22nd day of testing after 2.89 x 10^6 cycles, the seal failed with catastrophic leakage. Up to the time of failure static leakage was a trace, low temperature leakage was zero. The backup wore away allowing the elastomer to extrude and fail. This was a non-standard backup and was incorporated in an attempt to use a seal for which the molds were available. This backup performance should not be compared with any results of the backup ring screening tests.

Candidate RS 28 (3694-0998-0122-0304)

MATERIALS: Hytrel seal, nylon backup, nitrile O-ring.

CHARACTERISTICS: O-ring energized plastic lip seal with integral backup.

CONFIGURATION: See Figure 108.

RESULTS: See Figure 119. Two samples of this candidate were tested. The first sample had 58.86 cc dynamic leakage in the first seven days of testing with 20.8 cc on the day of removal. The seal exhibited linear scratches on the I.D. Removal of the actuator from the test setup disclosed severe wear of the rod against the end cap to the extent that the chrome plate was worn through. (See separate discussion of rod wear problem Section 6). The seal was replaced with a new RS 28 sample and the actuator was reassembled with a new replacement rod. The end cap was changed from 17-4 PH material to aluminum bronze. The second sample completed 14 days of testing with 81.05 cc static leakage, 7.5 cc low temperature, and 70 cc dynamic leakage. The seal exhibited a number of scratches on the I.D. The backup was in good condition. The rod had a wear pattern around the circumference corresponding to the area in contact with the nylon backup.

Candidate RS 29 (CEC5064-214-010)

MATERIAL: MIL-P-83461 compound elastomer, Revonoc 18158 backups.

CHARACTERISTICS: Square cross section elastomer with two stage backups.

CONFIGURATION: See Figure 109.

RESULTS: See Figure 120. The seal and backup were in good condition. Zero dynamic, zero static, and zero low temperature leakage were measured. The rod exhibited a light wear pattern under the backup contact area. The seal had a small crack around the ID on the edge next to the backup.

Figure 99. Candidate RS3 (7214-972-4780; Greene, Tweed)

Figure 100. Candidate RS7 (S33050-214P-18; W. S. Shamban)

Figure 101. Candidate RS13 (501-016-1109-01, Dowty, Ltd.)

Figure 102. Candidate RS20 (CEC 5056-214; C. E. Conover/G. K. Fling)

Figure 103. Candidate RS22 (TF831M-7214 Seal, M83461/1-318 O-Ring; Tetrafluor, Inc.)

Figure 104. Candidate RS24 (TF831-214-1 Seal, TF95-214 Backup, M83461/1 O-ring; Tetrafluor, Inc.)

Figure 105. Candidate RS25 (S30650-214-14 Seal, S33012-214-14 Backup, M83461/1 O-ring; W. S. Shamban)

Figure 106. Candidate RS26 (CEC 5058-214 Seal, CEC 5057-214 Backup M83461/1-214 O-ring; C. E. Conover)

Figure 107. Candidate RS27 (18701000 Special Standard, Parker Packings)

Figure 108. Candidate RS28 (3694-0998-0122-0304; Greene, Tweed)

Figure 109. Candidate RS29 (CEC 5064-214-010; C. E. Conover)

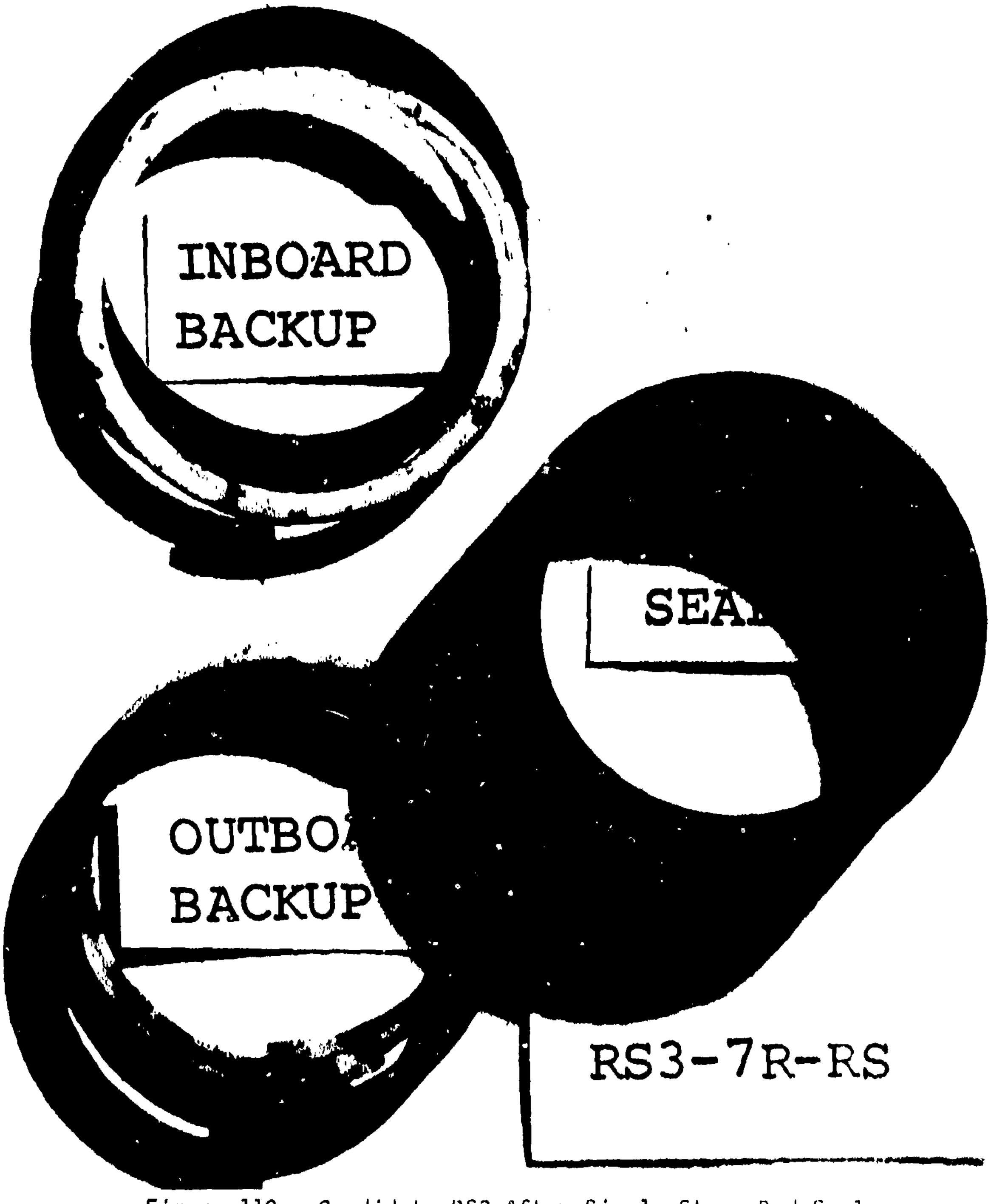


Figure 110. Candidate RS3 After Single Stage Rod Seal Screening Test. Seal is Fluoromer elastomer. Backups are two stage nylon and unfilled TFE.

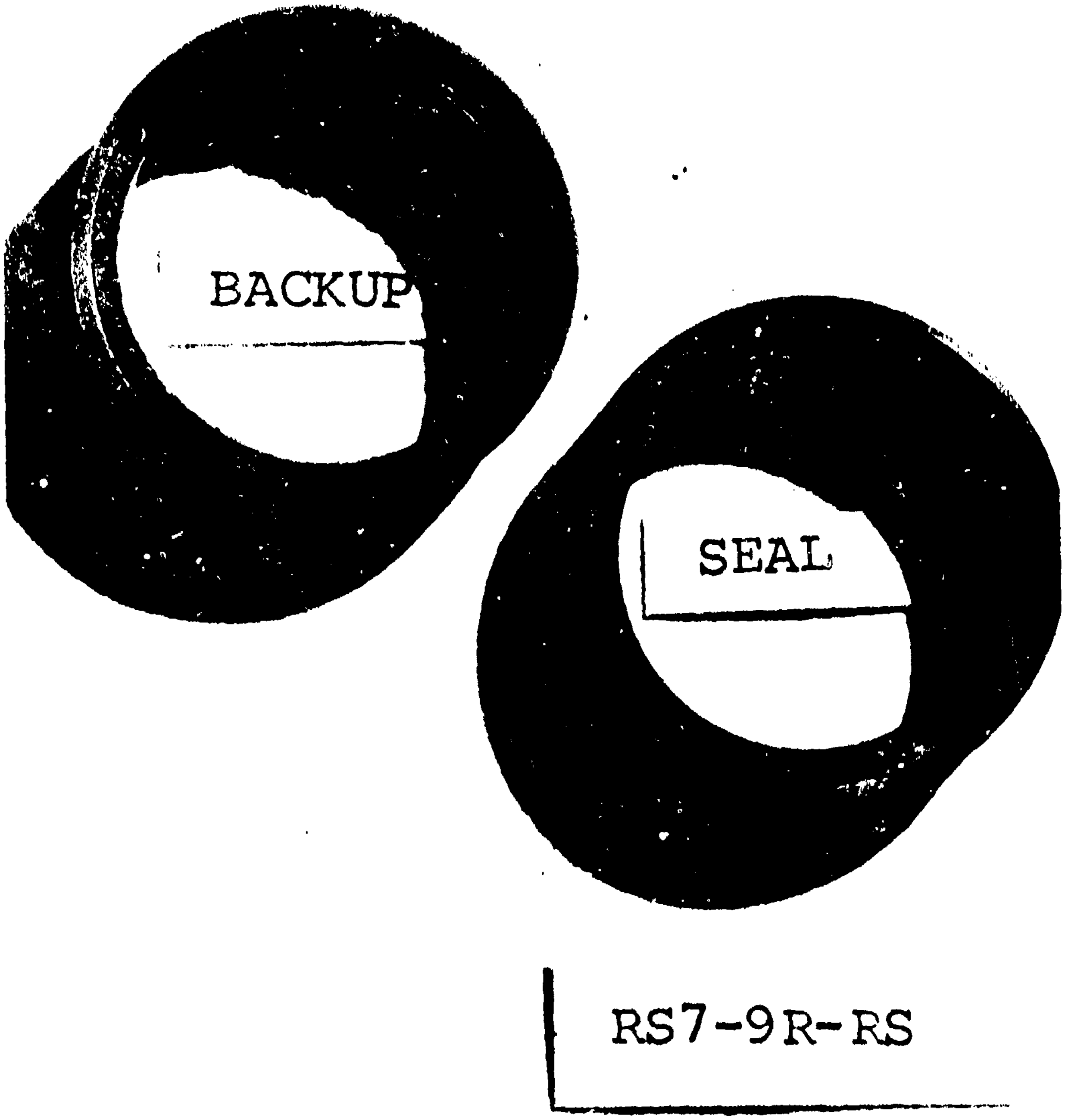


Figure 111. Candidate RS7 After Single Stage Rod Seal Screening Tests. Two piece backup and seal were in excellent condition.

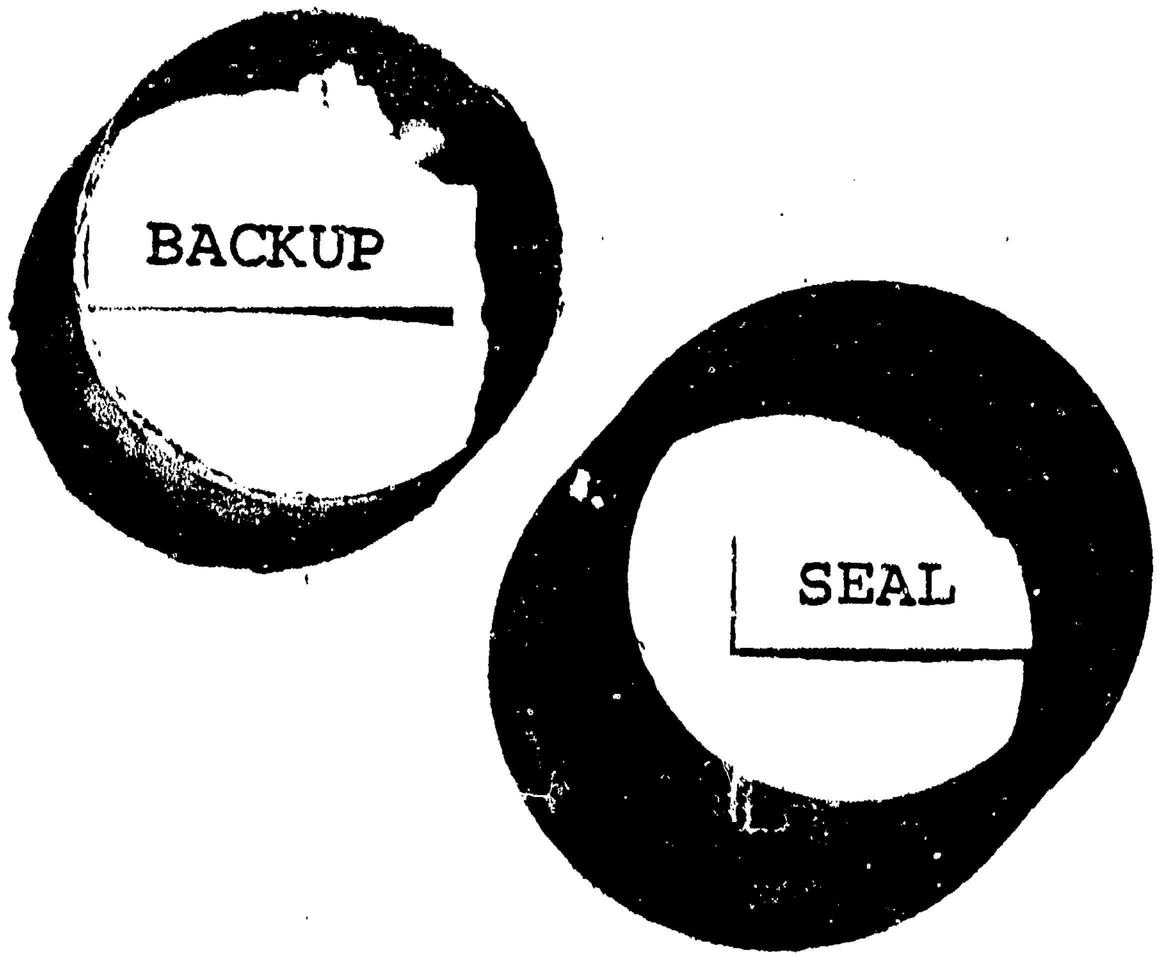


Figure 112. Candidate RS13 After Single Stage Rod Seal Screening Test. Seal is Dowty 1109 nitrile. Backup is unfilled TFE.

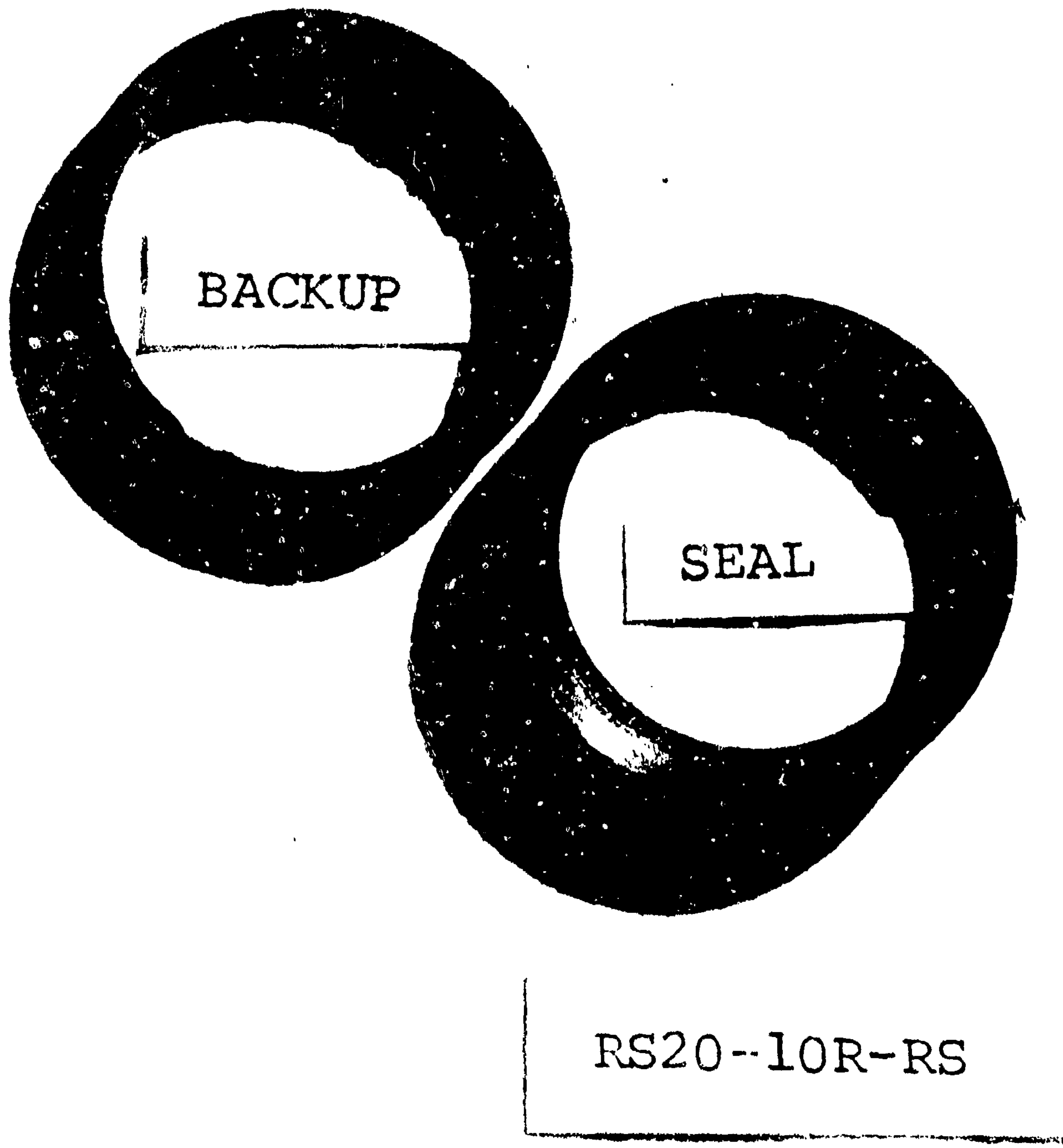


Figure 113. Candidate RS20 After Single Stage Rod Seal Screening Test. Trapezoid shape elastomer and backup had no leakage.

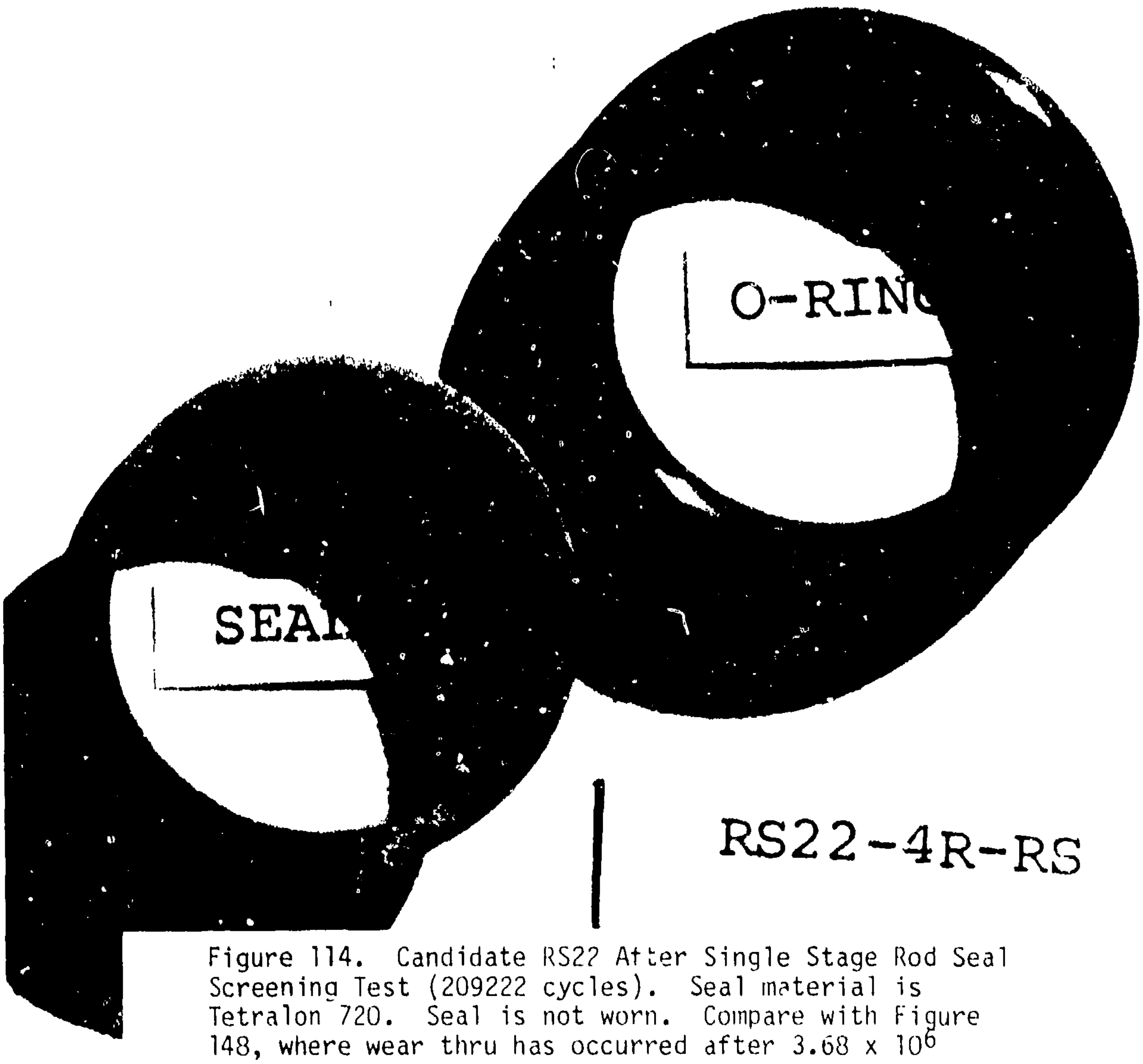


Figure 114. Candidate RS22 After Single Stage Rod Seal Screening Test (209222 cycles). Seal material is Tetralon 720. Seal is not worn. Compare with Figure 148, where wear thru has occurred after 3.68 x 10^6 cycles.

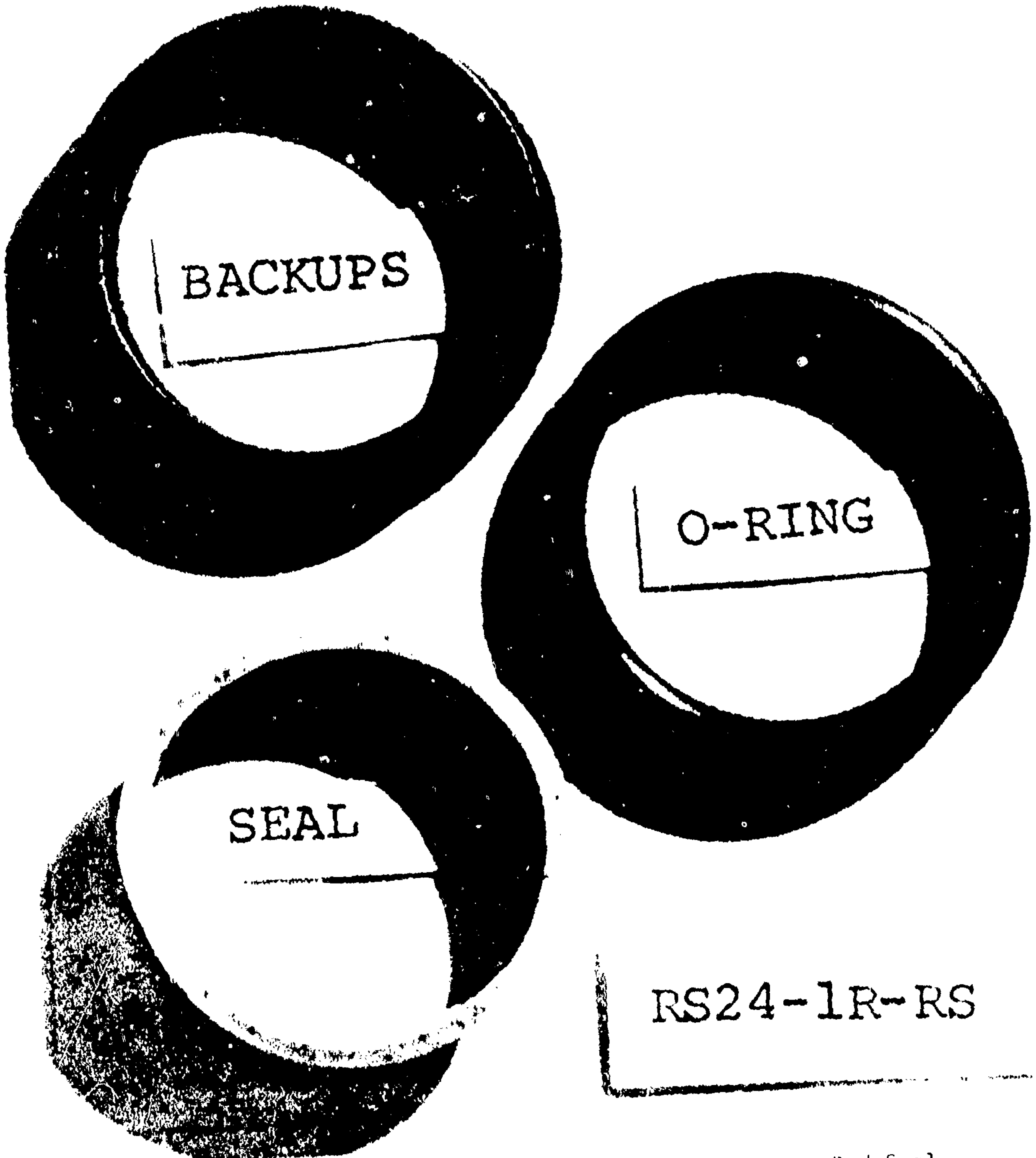


Figure 115. Candidate RS24 After Single Stage Rod Seal Screening Test. Seal and backup material is Tetralon 720.

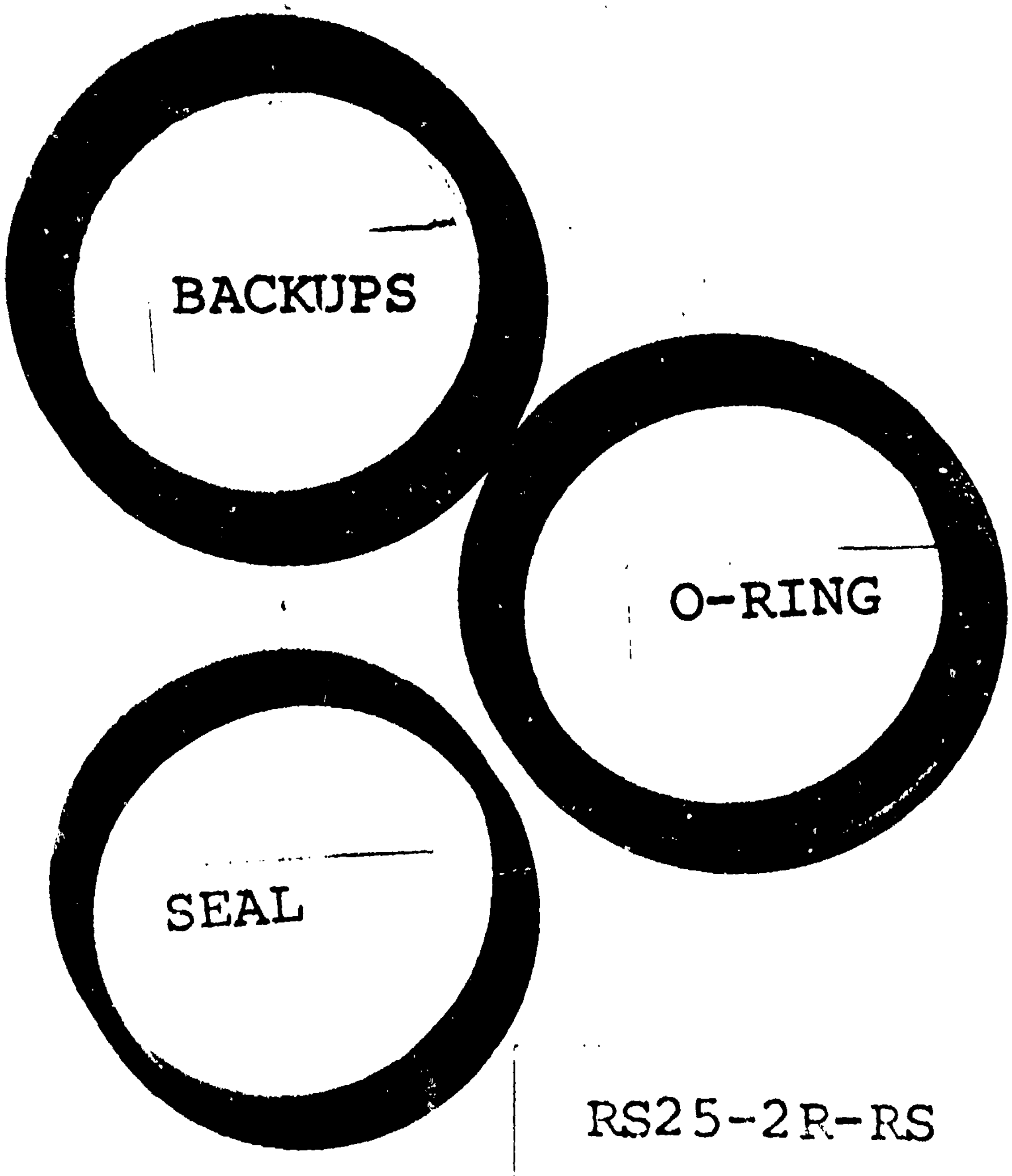


Figure 116. Candidate RS25, After Single Stage Rod Seal Screening Test. Seal and backup material is Shamban Code 14.

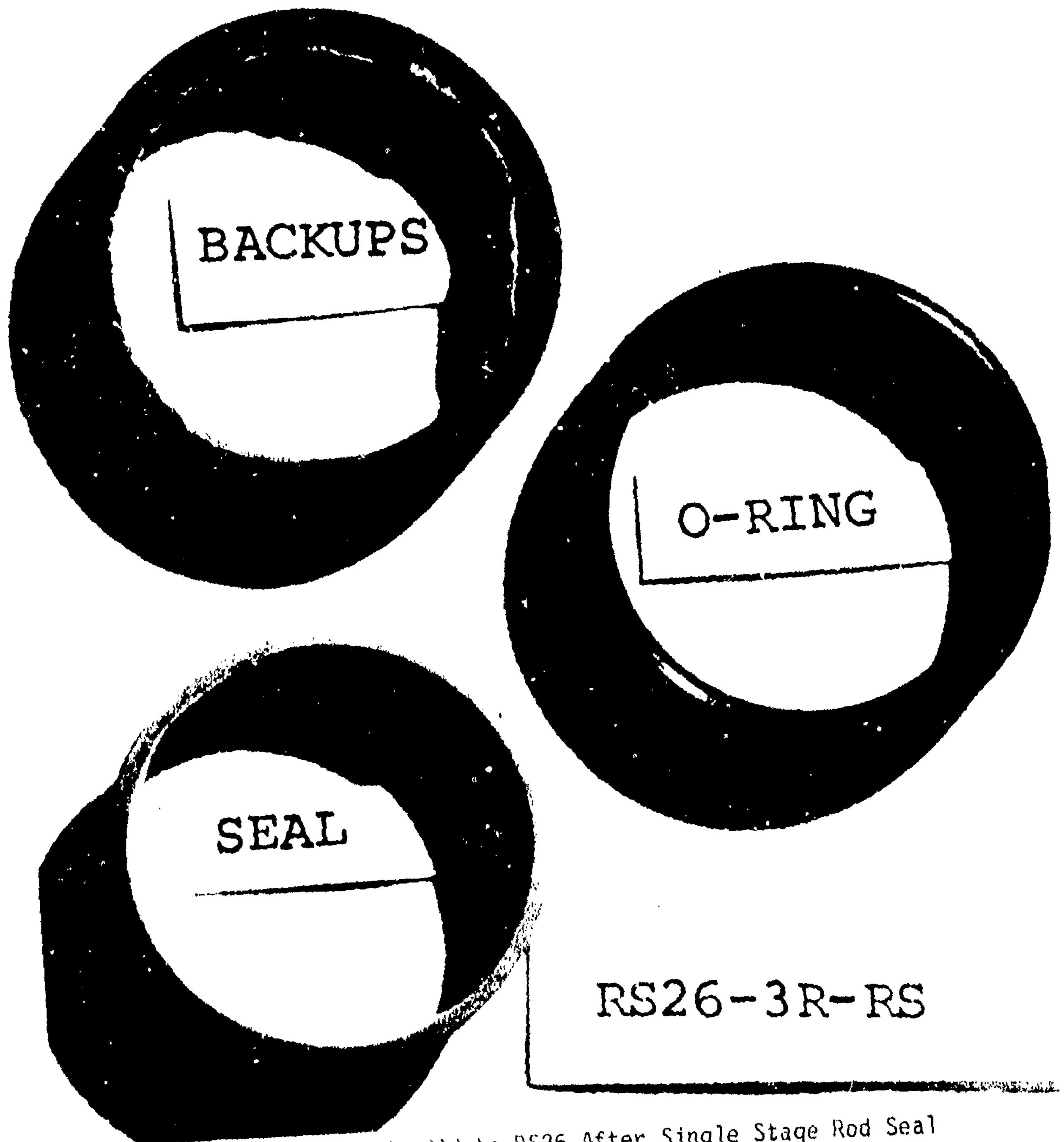


Figure 117. Candidate RS26 After Single Stage Rod Seal Screening Test. Seal is Revonoc 6200, backups are Revonoc 18158.

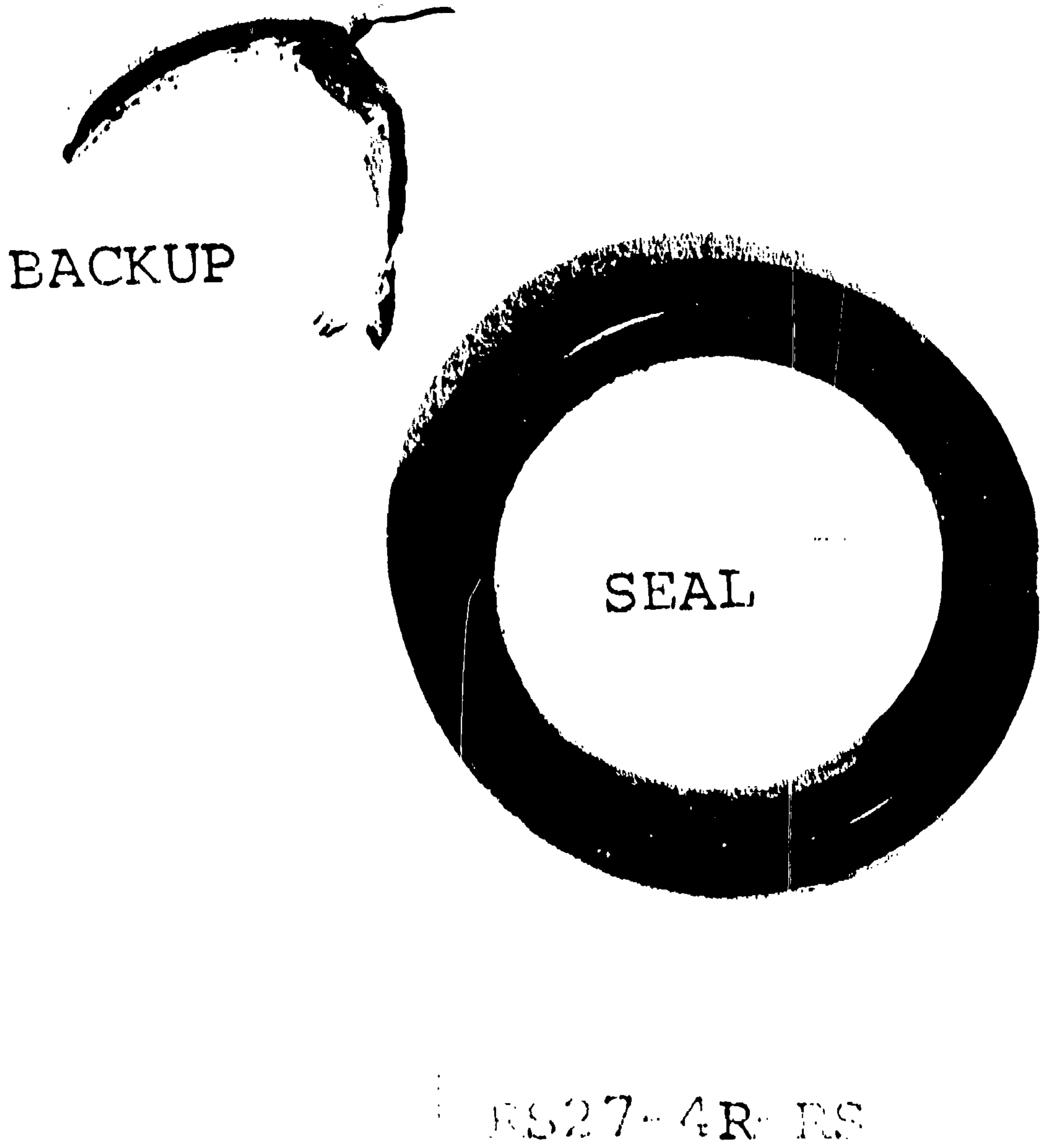


Figure 118. Candidate RS27 After Single Stage Rod Seal Screening Test. Non-standard unfilled TFE backup failed at 2.89 x 10^6 cycles.

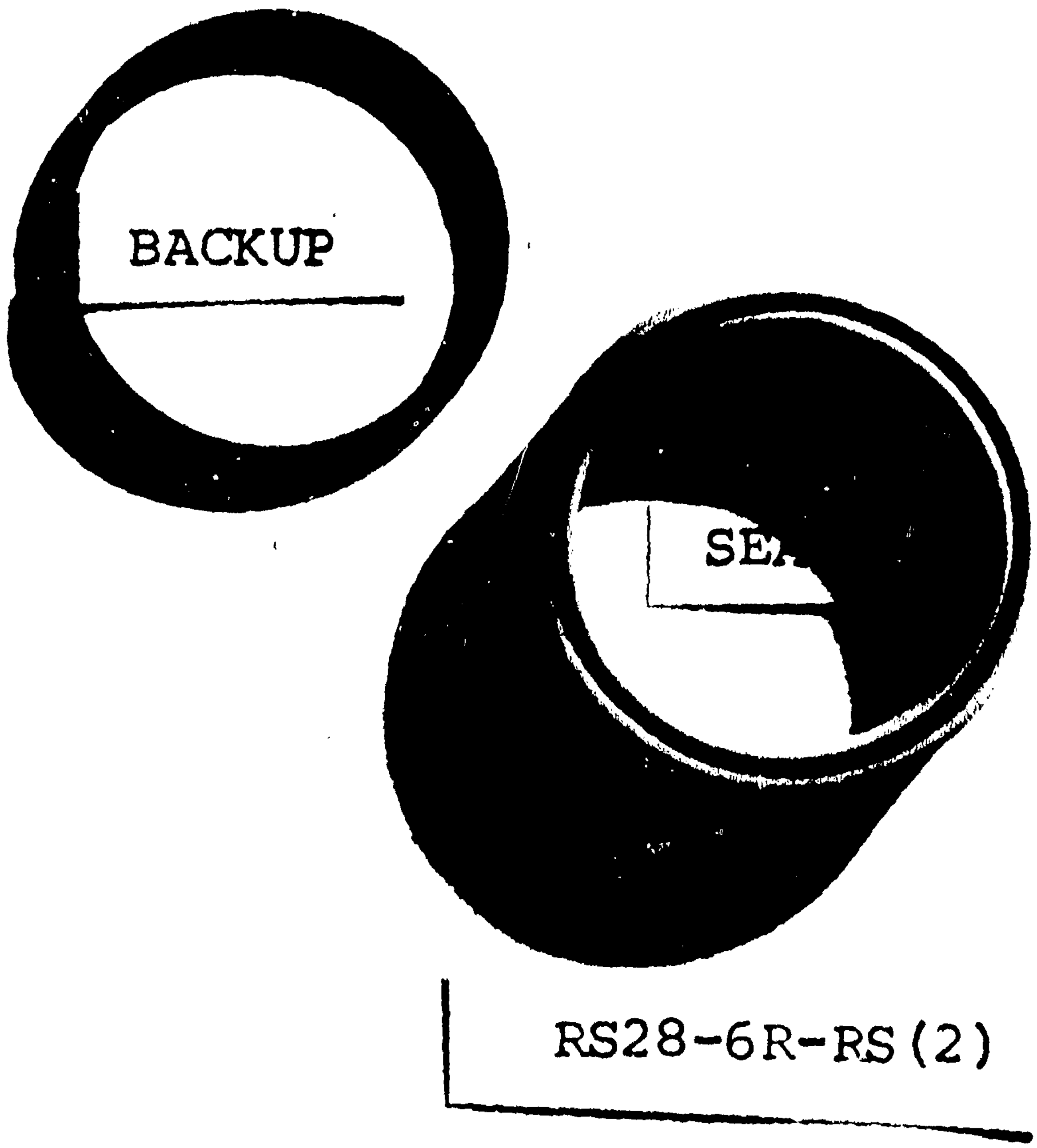


Figure 119. Candidate RS28 After Single Stage Rod Seal Screening Test. Seal is Hytrel. Backup is nylon.

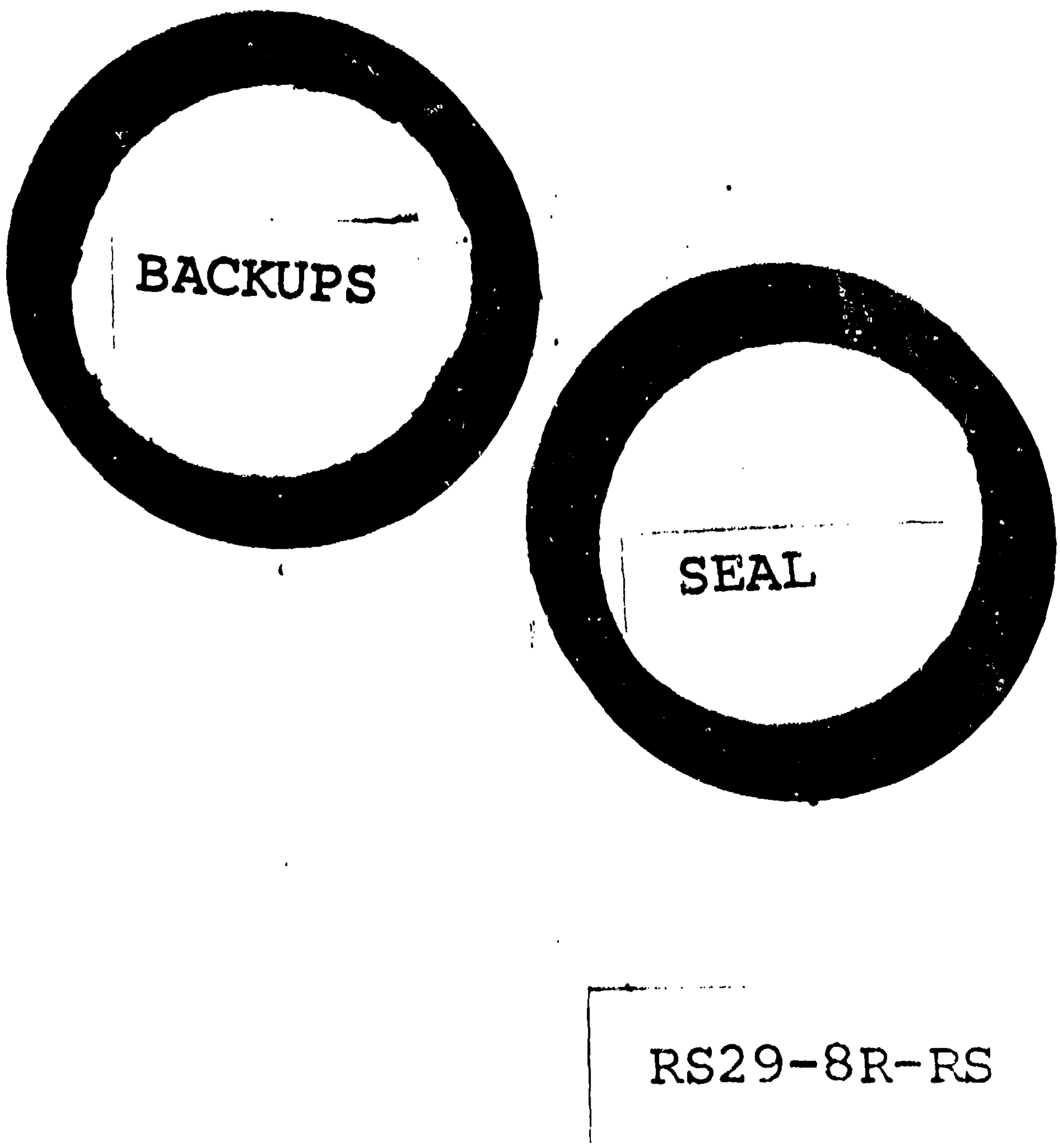


Figure 120. Candidate RS29 After Single Stage Rod Seal Screening Test. Two stage Revonoc 18158 backups with square cross section elastomer.

3.4 Two Stage Rod Seals

A total of 10 configurations were tested. All candidates completed 3.68×10^6 cycles of the spectrum with oil temperatures of 250°F and air temperatures of 170°F. A weekly -65°F leakage test was conducted. Static leakage was collected overnight and on weekends when the test system was shut down. The candidates were tested in torsion bar loaded hydraulic cylinders to simulate air loads. The tests evaluated two stage plastic and elastomeric seals in vented, semi-vented, and unvented installations.

An evaluation of results for the three types of two stage installation - vented, semi-vented, and unvented gives the following:

- 2 of 3 semi-vented installations did not leak.
- 1 of 3 vented installations did not leak
- 3 of 4 unvented installations did not leak
- 1 of 2 installations with a cap seal outboard did not leak.
- 5 of 8 installations with an elastomer seal outboard did not leak.

An evaluation of candidate TRS 18 which was tested in each of the three types of installation gives the following:

- The inboard seal was not worn thru on the semi-vented installation, but was worn and cracked on the vented and unvented installation.

- No leakage occurred with the unvented installation.

- Rod wear due to the nylon backups on the outboard "T" seal was least with the semi-vented installation.

Upon disassembly of each two stage rod seal installation, an accumulation of soft, black oily residue was noted in the cavity between seals in all cases. This appears to be a normal occurrence and is not considered to be detrimental. Figure 121 shows three end caps and the appearance of the residue.

Table 12 summarizes the results on performance of all two stage rod seal candidates. Specific results for each candidate are as follows:

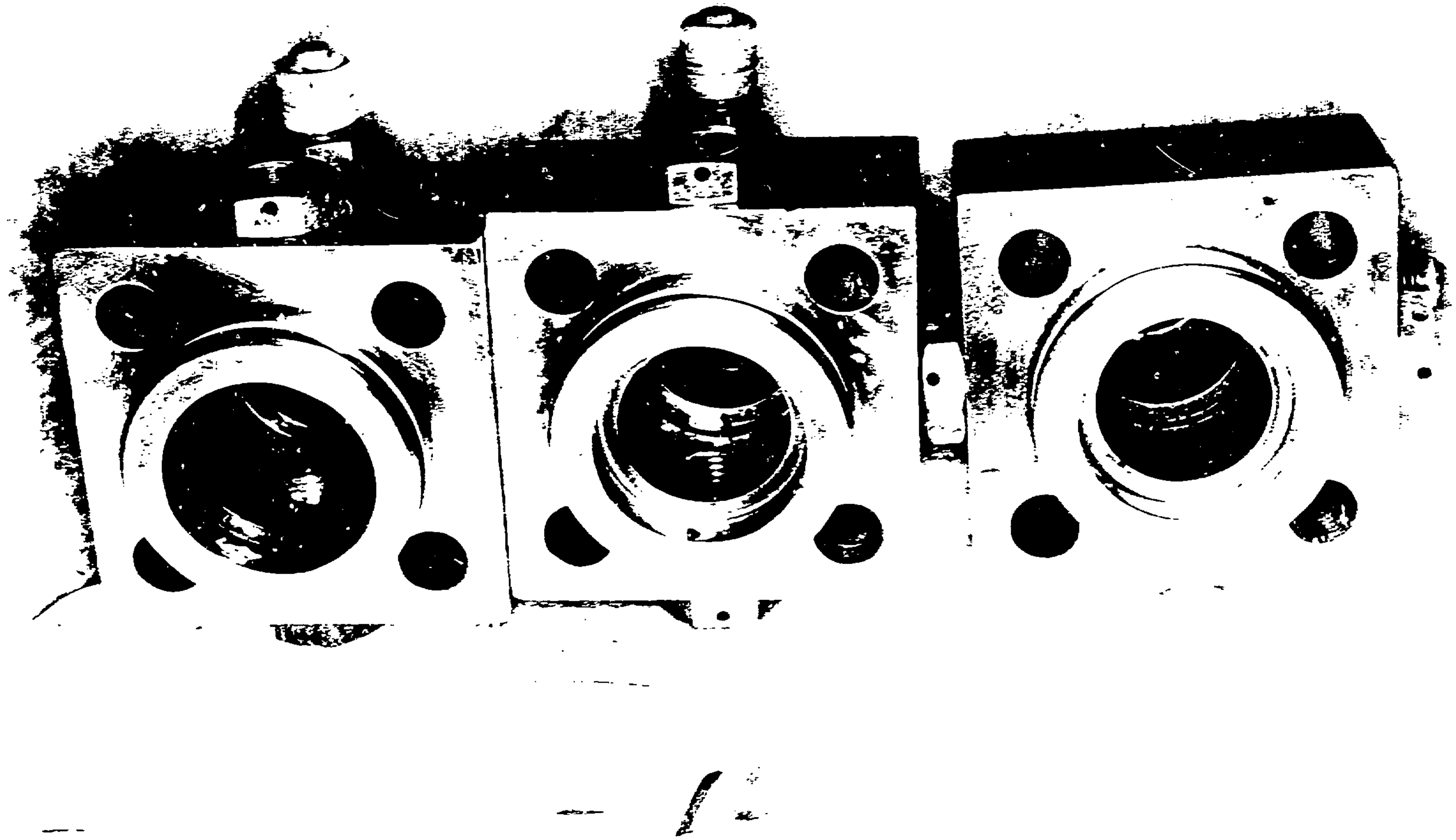


Figure 121. End Caps in Two Stage Rod Seal Screening Test. Normally have soft oily seal residue between seals.

TABLE 12. SUMMARY OF TWO STAGE ROD SEAL SCREENING TESTS

ASSY NO	CANDIDATE NO.	OUTBOARD SEAL CONFIG.	INBOARD SEAL CONFIG.	LEAKAGE (SEE PARA 7.0)	SEAL CONDITION		ROD CONDITION
					INBOARD	OUTBOARD	
3	TRS4-SV	Trapezoid Elastomer Seal	Trapezoid Elastomer Seal	No	Good	Good	Light wear
8	TRS6-UV	O-ring with 2 stage backups	O-ring with single stage backups	No	Good	Good	No wear
10	TRS8-UV	Elastomer seal with integral backup	Elastomer seal with integral backup	372 ml	backup worn thru	Sealing lip cracked, backup worn	light wear
5	TRS13-V	Conohex Cap Seal	Conohex Cap Seal	Yes	Good	Good	Light wear
1	TRS18-SV	"T" Seal with 2 stage backups	Cap seal with backups	Yes	Good	Good	Light Wear
7	TRS18-UV	"T" seal with 2 stage backups	Cap seal with backups	No	Cracked and separating on ID.	Good	Severe wear
4	TRS18-V	"T" Seal with 2 stage backups	Cap seal with backups	Yes	Worn thru	Good	Moderate to severe wear
6	TRS19-V	"Hat" seal with Elastomer lip	3/16 in cross-section O-ring and cap seal	No	Cracked and separating on ID	Good	Moderate wear
9	TRS20-UV	"Hat" seal with Elastomer lip	"Hat" seal with Elastomer lip	No	Good	Good	No wear, "Lapped" appearance
2	TRS21-SV	"Plus" cap seal	"Plus" cap seal	No	Good	Good	Light wear

Candidate: TRS4-SV

MATERIAL: The inboard and outboard seals were identical with MIL-P-83461 elastomer and Revonoc 18158 backups.

CHARACTERISTICS: A trapezoid shaped elastomer loads a mating trapezoid shaped backup into the rod. This was a semi-vented installation.

CONFIGURATION: See Figure 122.

RESULTS: See Figures 132 and 133. The inboard and outboard seals had no appearance of wear. The backups inner diameters of .9903 and .996 had yielded to .998 corresponding to rod diameter. Rod wear was very light. There was no evidence of external leakage. Approximately 2 to 3 ml of thick black residue had accumulated between the seals. Diametral clearance for the outer seal was .0031 and for the inner seal was .0035.

Candidate TRS6-UV

MATERIAL: The inboard and outboard seals are identical in material. The backups are Revonoc 18158, the O-ring is MIL-P-83461 Elastomer.

CHARACTERISTICS: This two stage seal represents the use of O-rings with a high performance backup from the backup ring screening tests. The inboard seal has a backup on each side to protect the O-ring from extrusion in the event that pressure in the cavity between the seals is greater than the pressure in the retract side of the actuator. The outboard seal has both backups outboard for maximum O-ring protection. This was an unvented installation.

CONFIGURATION: See Figure 123.

RESULTS: See Figures 134 and 135. Both inboard and outboard O-rings were in excellent condition. The backup showed some wear with the outer backup on the inboard seal showing the most wear. Cross-section was .1214 before test and .1033 after test. There was no rod wear. There was no external leakage. The cavity between the seals had an accumulation of black residue similar to that found in other end caps. Diametral clearance for the outboard seal was .0033 and for the inboard seal was .0023.

Candidate TRS8-UV

MATERIAL: Unfilled TFE backup with Dowty nitrile compound 1109 elastomer for both inboard and outboard seals.

CHARACTERISTICS: This seal is configured to give radial loading on the backup against the rod and has an elastomer lip which contacts the rod. This was an unvented installation.

CONFIGURATION: See Figure 124.

RESULTS: See Figures 136 and 137. The backup on the inboard seal was worn thru at one location. The backup on the outboard seal was severely worn completely around its circumference and the sealing lip on the elastomer was fatiguing and tearing. This seal leaked erratically throughout the test for a total of over 372 ml. The rod surface finish had a slight "lapped" appearence. Diametral clearance for the inboard seal was .0027 and for the outboard seal was .0052.

Candidate TRS13-V

MATERIAL: The inboard and outboard seals were identical with Revonoc 6200 cap seals and Revonoc 18158 backups. The elastomer was MIL-P-83461 compound.

CHARACTERISTICS: The seal has the feature of a hexagonal cross section elastomer with a fairly wide radial energizing area against the rod. The backup configuration mates with the cap seal and elastomer in a manner to load the cap seal against the rod and the backup against the ID of the groove. The cavity between the seals was vented.

CONFIGURATION: See Figure 125.

RESULTS: See Figures 138 and 139. Both the inboard and outboard seal were in excellent condition. The ID of the cap seals was less than .982 before test and .9903 to .996 after test which was less than the rod diameter of .998. The rod had light wear. Wear was not uniform around the circumference of the rod indicating not all side loading was eliminated on the cylinder. There was evidence of external leakage. Diametral clearance was .0024 for both inboard and outboard seals.

Candidate TRS18-SV

MATERIAL: The outboard seal was Fluoromer elastomer with two stage scarf cut backups. The backup next to the elastomer was unfilled TFE, the second backup was nylon. The inboard seal had backups and cap seal of Tetralon 720; O-ring of MIL-P-83461 elastomer.

CHARACTERISTICS: No backup width cap seal with single backups inboard; elastomer "T" seal outboard. Cavity between seals is vented back to retract port of cylinder through a check valve hereafter referred to as a semi-vented installation.

CONFIGURATION: See Figure 126.

RESULTS: See Figures 140 and 141. Inboard seal had minimum wear with no evidence of cracking or splitting around circumference on inner diameter of cap seal. Outboard seal had minimum wear, with a very shallow axial wear pattern around the inner diameter sealing surface. The staged nylon/TFE backups showed no wear. The rod had a light to moderate axial wear pattern around the circumference corresponding to the areas most frequently contacted by the nylon backup rings on the outboard seal. Diametral clearance for the outboard seal was .0035 and for the inboard seal was .0025. There was evidence of some external leakage. See separate discussion of leakage collection in paragraph 7.0. Two to four ml of soft black residue had accumulated between seals.

Candidate TRS 18-V

MATERIALS: Same as TRS 18-SV

CHARACTERISTICS: Same as TRS 18-SV except cavity between seals was vented back to system return (90 psi) thru a restrictor, hereafter called a vented installation.

CONFIGURATION: See Figure 127.

RESULTS: See Figures 142 and 143. The cap seal on the inboard seal was worn thru and extruded away at one location on the ID. The entire ID sealing surface appeared to be worn sufficiently that a shallow crack was forming around the ID. The backups and O-ring were not worn. The outboard seal was in excellent condition. It was noted on disassembly that the inner TFE backup on the outboard side of the "T" seal had been incorrectly installed with the radius edge away from the elastomer (see configuration sketch). The tip of the TFE backup was curled over the OD of the outer backup. The rod had a moderate to severe axial wear pattern around the circumference of the rod in the area most frequently contacted by the nylon backups on the outboard seal. This wear pattern was more severe than the wear pattern from TRS 18-SV with identical seals but with semi-vented installation. The seal did leak externally. The diametral clearance for the outboard seal was .0023 and for the inboard seal was .0013. Approximately 3 to 4 ml of thick black residue had accumulated between seals.

Candidate TRS 18-UV

MATERIALS: Same as TRS 18-SV

CHARACTERISTICS: Same as TRS 18-SV except the cavity between the seals was not vented in any manner, hereafter called an unvented installation.

CONFIGURATION: See Figure 128.

RESULTS: See Figures 144 and 145. The cap seal on the inboard seal was cracked around the ID and had begun to separate. The O-ring and backups were in excellent condition. The outboard seal and backups had minimum wear. The rod had a very severe axial wear pattern around the circumference corresponding to the areas most frequently contacted by the nylon backups on the outboard seal. There was no evidence of external leakage. The cavity between the seals had relatively small amount of residue collected when compared to TRS 18-SV or -V. The diametral clearance for the outboard seal was .0048 and for the inboard seal was .0013.

Candidate TRS19-V

MATERIAL: The inboard seal had a Tetralon 720 cap seal with MIL-P-83461 elastomer O-ring. The outboard seal had a backup of Shamban compound 18 and elastomer of MIL-P-83461 compound.

CHARACTERISTICS: The inboard seal corresponds to a -318 no backup width gland per ARP 568. The O-ring is a 3/16 inch cross section to give a wide radial loading area against the cap seal. The outboard seal has a two piece "L" shape backup which acts as a cap seal when the seal experiences pressure. The elastomer is configured to give a wide radial loading area against the backup and also has an elastomer lip seal against the rod. This was a vented installation.

CONFIGURATION: See Figure 129.

RESULTS: See Figures 146, 147 and 148. The inboard cap seal had cracked and split almost entirely around the ID. The outboard seal had no evidence of wear. The rod had a moderate axial wear pattern on the circumference corresponding to the area contacted most frequently by the outboard seal. Rod wear was light under the inboard seal. Rod wear was more pronounced on one side indicating not all side loading was eliminated. There was no evidence of external leakage. The outboard seal had .0028 diametral clearance. The inboard seal had .0018 diametral clearance. The cavity between the seals was relatively clear of residue.

Candidate TRS20-UV

MATERIAL: Molybdenum disulfide filled Turcon (compound 99 from W. S. Shamban) for the backup and MIL-P-83461 elastomer on both seals.

CHARACTERISTICS: Both the inboard and outboard seals were identical. The seal consists of a two piece "L" shape backup which acts like a cap seal when the seal is pressurized. The elastomer is configured to give a wide radial loading area against the backup and also has an elastomer lip seal against the rod. This was an unvented installation.

CONFIGURATION: See Figure 130.

RESULTS: See Figures 149 and 150. Both seals were in excellent condition. A slight wear pattern on the ID of the inboard seal indicates it was functional during the test. The outboard seal did not have a similar pattern. There was no evidence of external leakage. The rod surface was not worn but did display a "lapped" appearance on areas with the most frequent contact with the seals. The diametral clearance for the inboard seal was .003 and for the outboard seal was .0031.

Candidate TRS 21-SV

MATERIAL: Both the inboard seal and the outboard seal were of Shamban compound 19. The backup rings were of the same material. The elastomer was of MIL-P-83461 compound.

CHARACTERISTICS: The cap seal used both inboard and outboard has a molded elastomer that distributes the radial energizing load on the rod over a larger area of the cap seal to reduce local wear of the cap seal. This was a semi-vented installation.

CONFIGURATION: See Figure 131.

RESULTS: See Figures 151 and 152. Both the inboard and outboard cap seal, backups, and elastomers had minimum wear. The rod had a light to moderate circumferential axial wear pattern which was most pronounced in the area contacted by both seals during cycling. There was no evidence of leakage. Very little residue had collected between the seals. Diametral clearance for the outboard seal was .0039 and for the inboard seal was .0022. The bore of the end cap had an unusual very smooth "lapped" wear pattern.

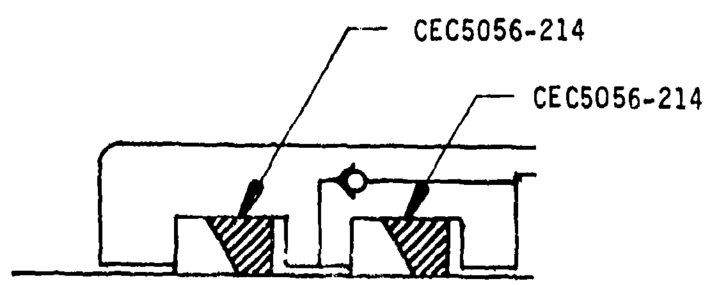


Figure 122. TRS4-SV Two Stage Rod Seal

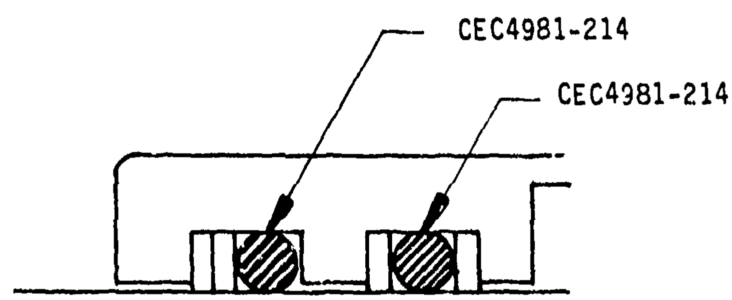


Figure 123. TRS6-UV Two Stage Rod Seal

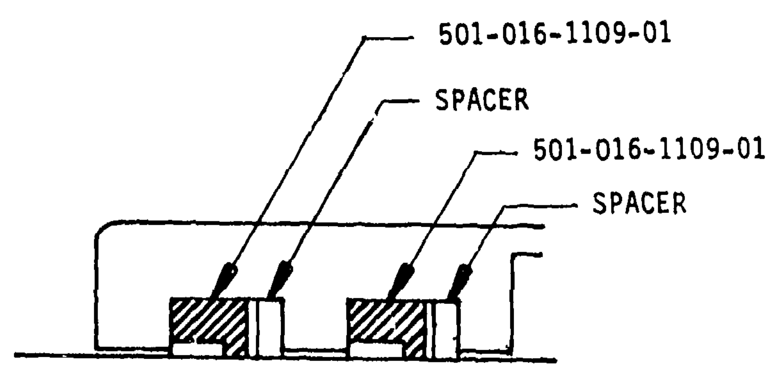


Figure 124. TRS8-UV Two Stage Rod Seal

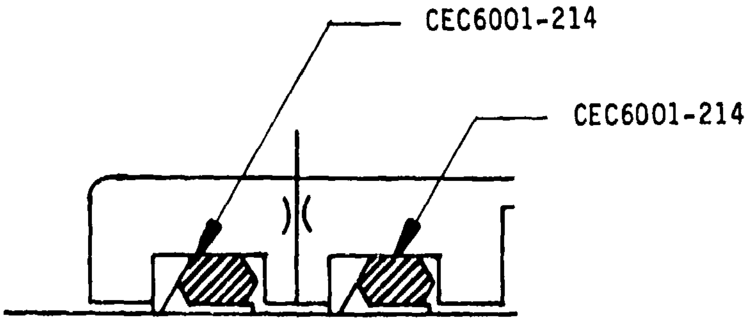


Figure 125. TRS13-V Two Stage Rod Seal

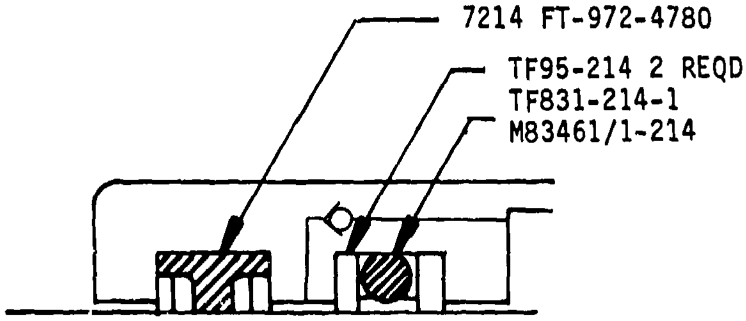


Figure 126. TRS18-SV Two Stage Rod Seal

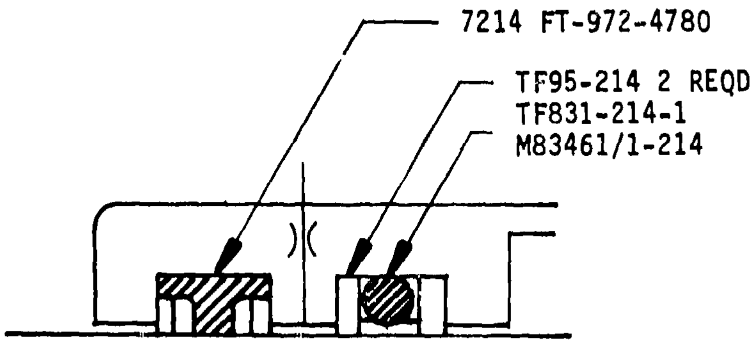


Figure 127. TRS18-V Two Stage Rod Seal

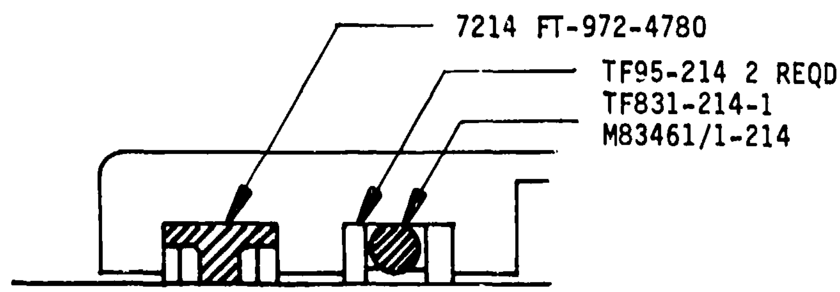


Figure 128. TRS18-UV Two Stage Rod Seal

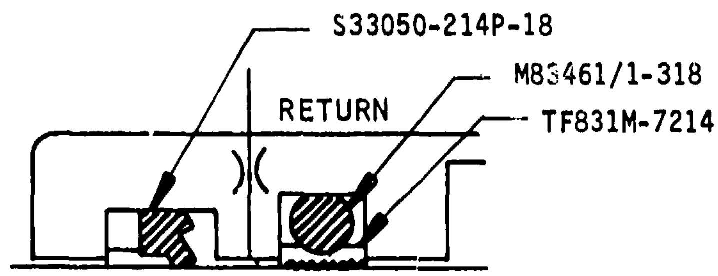


Figure 129. TRS19-V Two Stage Rod Seal

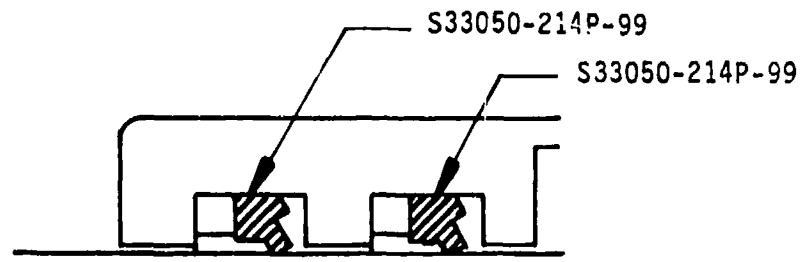


Figure 130. TRS20-UV Two Stage Rod Seal

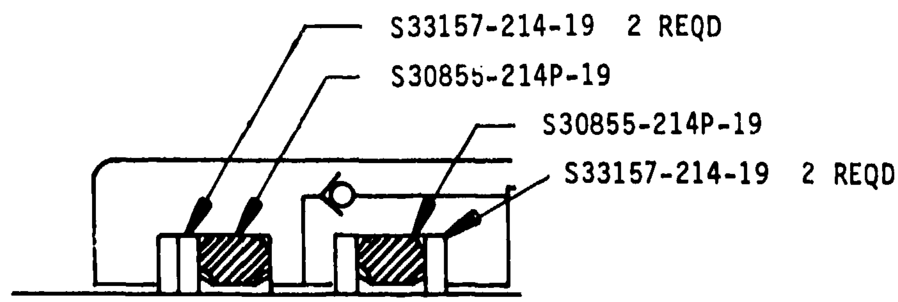


Figure 131. TRS21-SV Two Stage Rod Seal

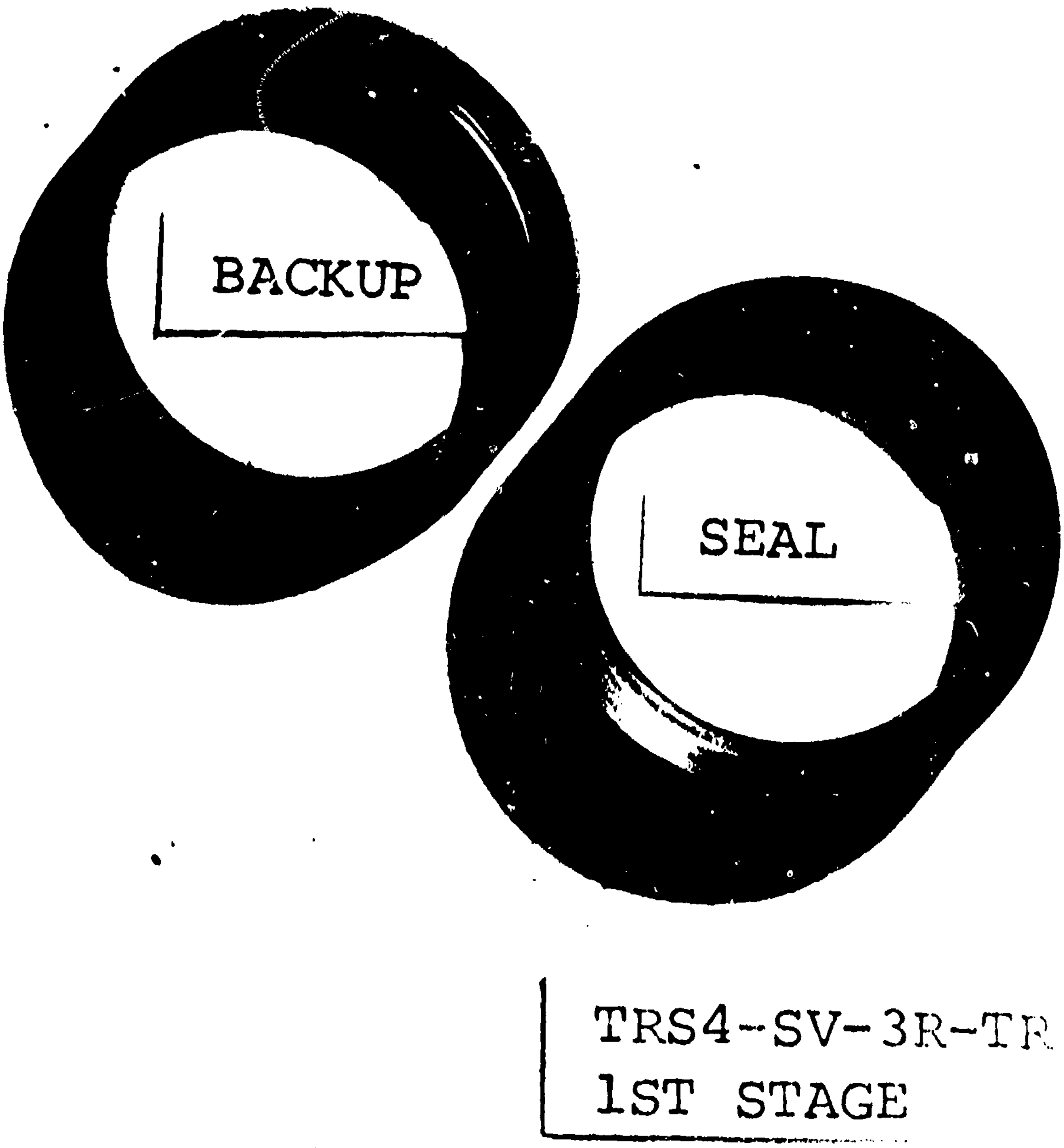


Figure 132. Candidate TRS4-SV (1st Stage) After Two Stage Rod Seal Screening Test. Trapezoid shape elastomer and backup had very little wear.

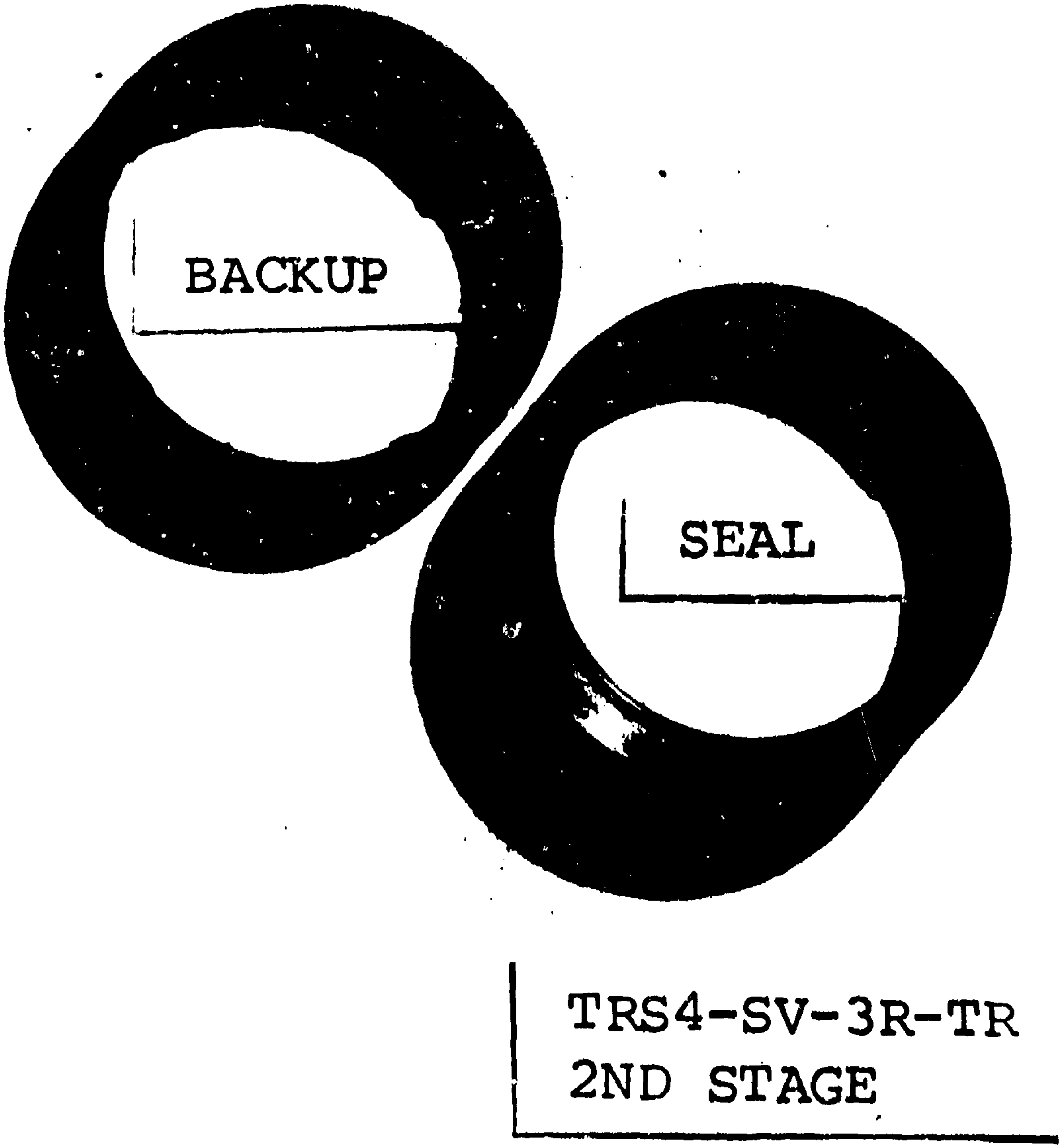


Figure 133. Candidate TRS4-SV (2nd Stage) After Two Stage Rod Seal Screening Test. Seal had no leakage during test.

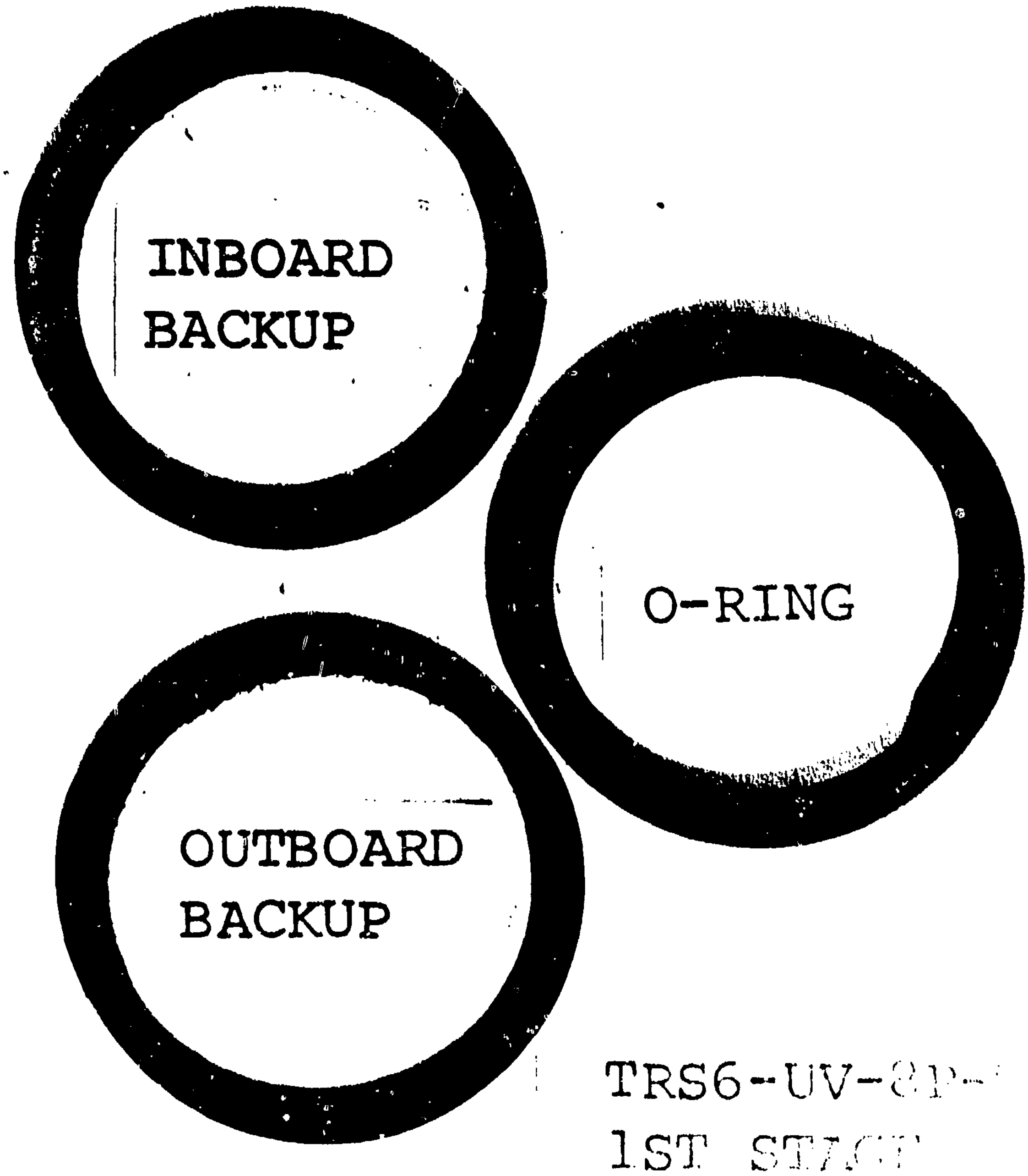


Figure 134. Candidate TRS6-UV (1st Stage) After Two Stage Rod Seal Screening Test. O-ring is in excellent condition.

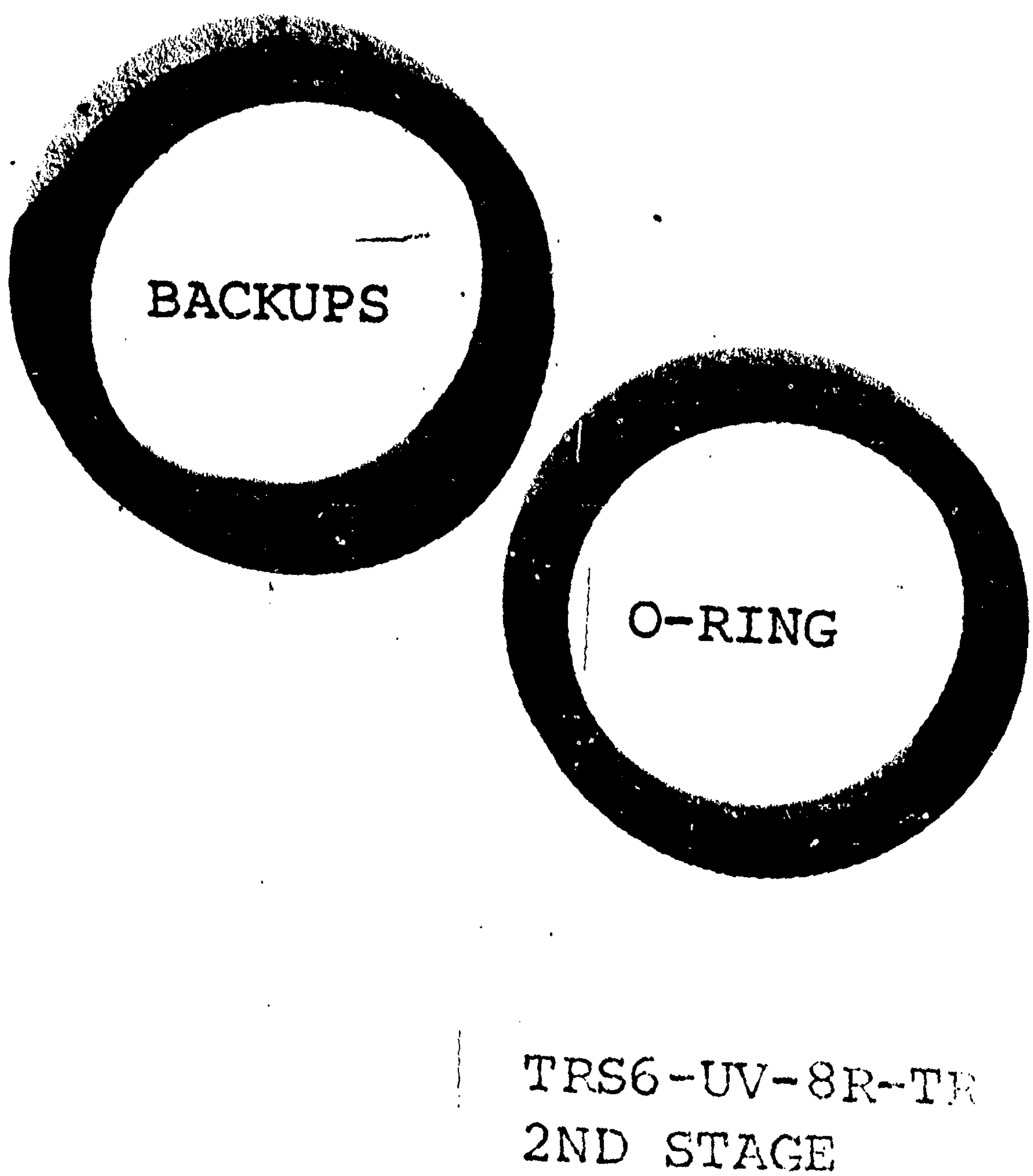


Figure 135. Candidate TRS6-UV (2nd Stage) After Two Stage Rod Seal Screening Test. There was no external leakage with this two stage installation.

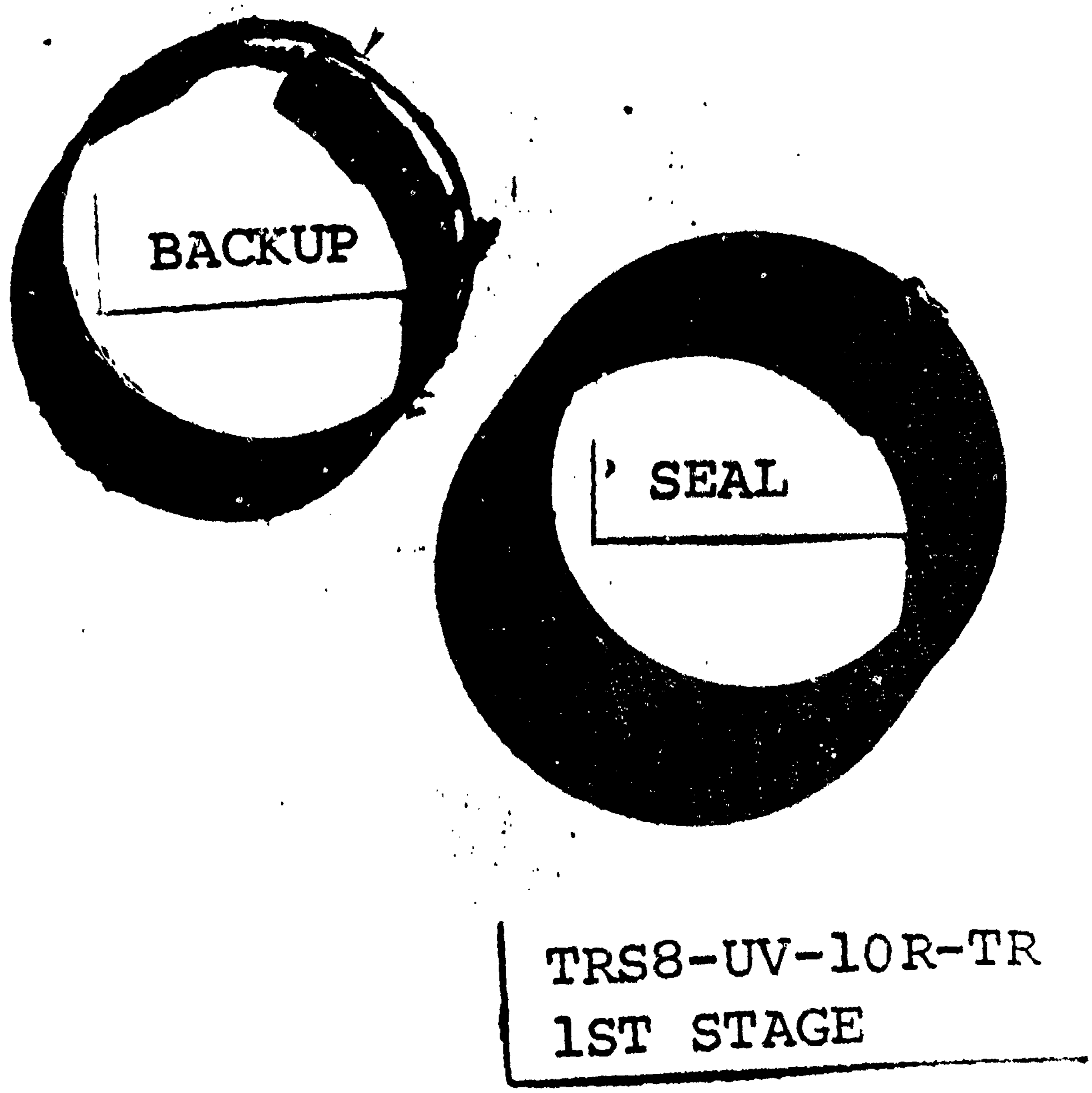


Figure 136. Candidate TRS8-UV (1st Stage) After Two Stage Rod Seal Screening Test. Arrow denotes area of backup which has worn through.

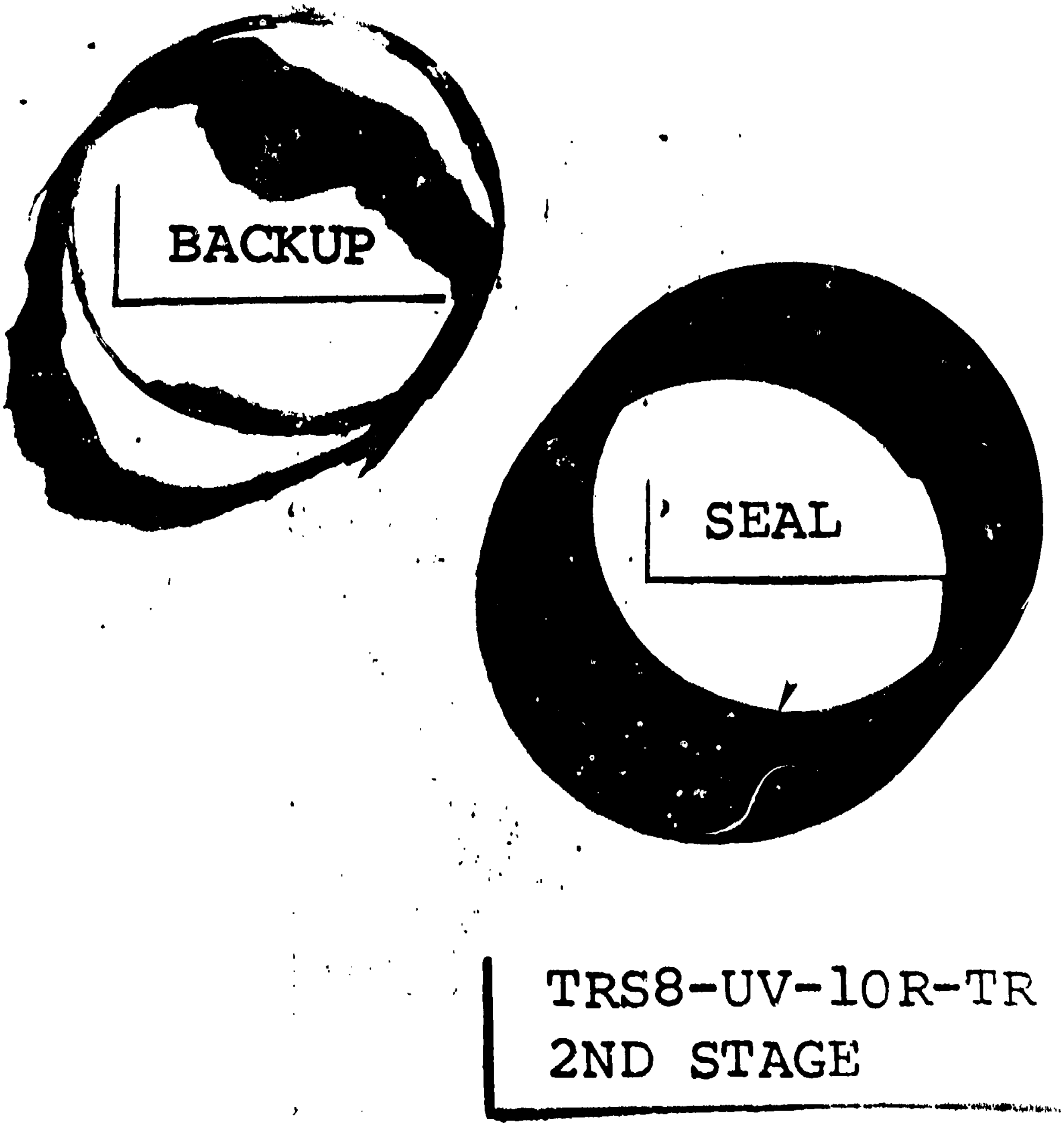


Figure 137. Candidate TRS8-UV (2nd Stage) After Two Stage Rod Seal Screening Test. Arrow shows where tear is beginning on sealing lip.

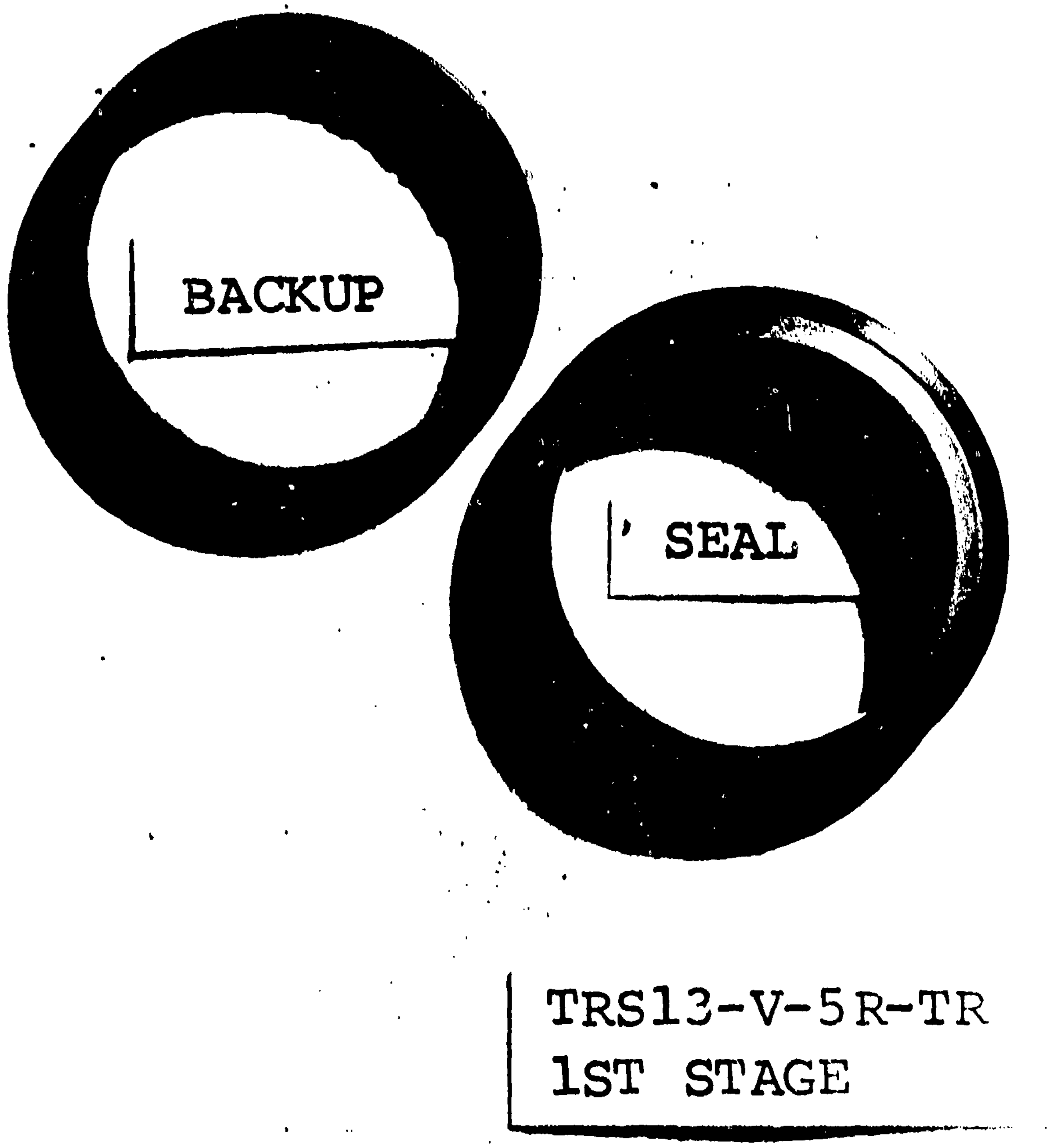


Figure 138. Candidate TRS13-V (1st Stage) After Two Stage Rod Seal Screening Test. Seal and backup were in excellent condition after test.

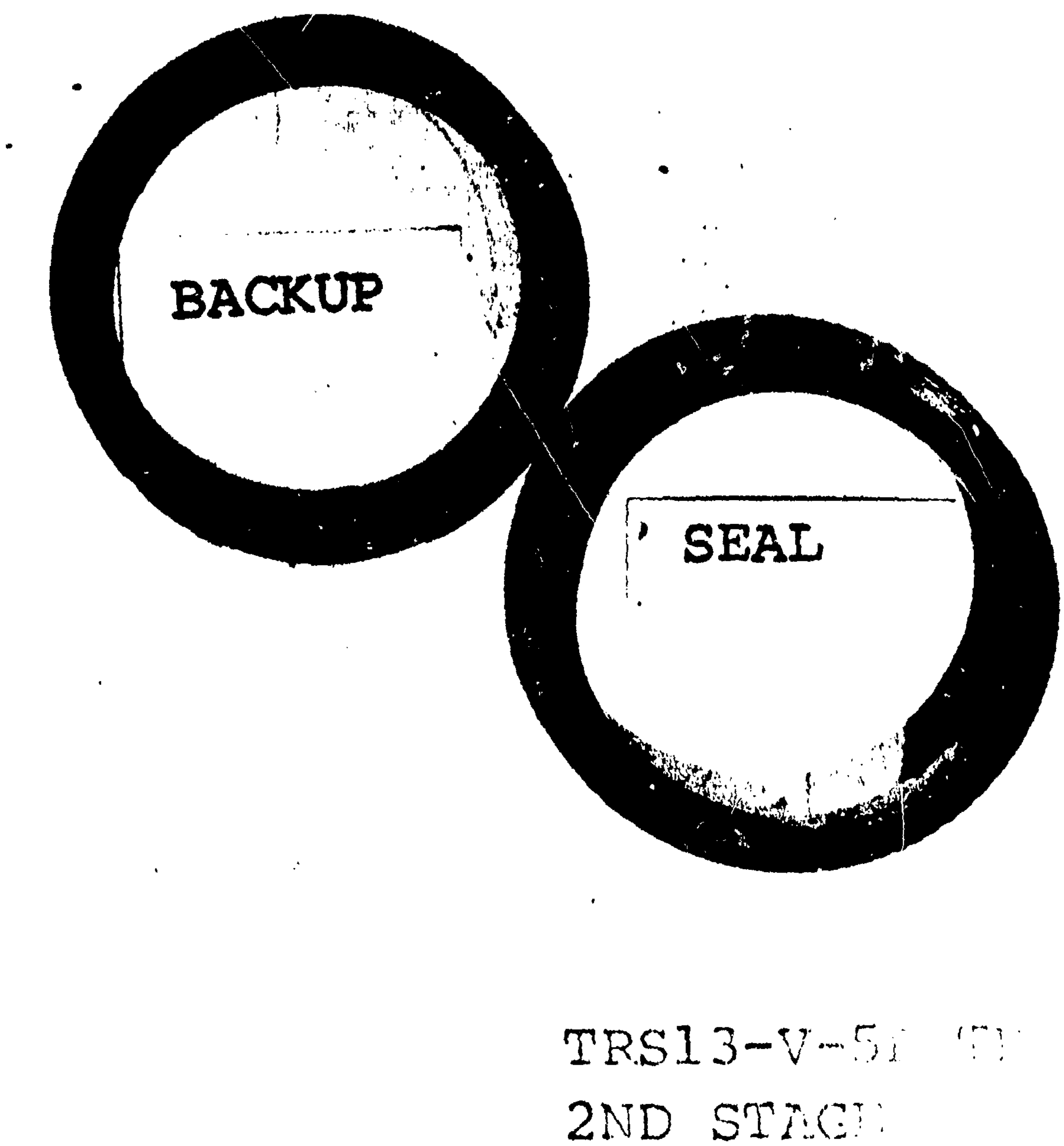


Figure 139. Candidate TRS13-V (2nd Stage) After Two Stage Rod Seal Screening Test. Seal and backup were in excellent condition after test.

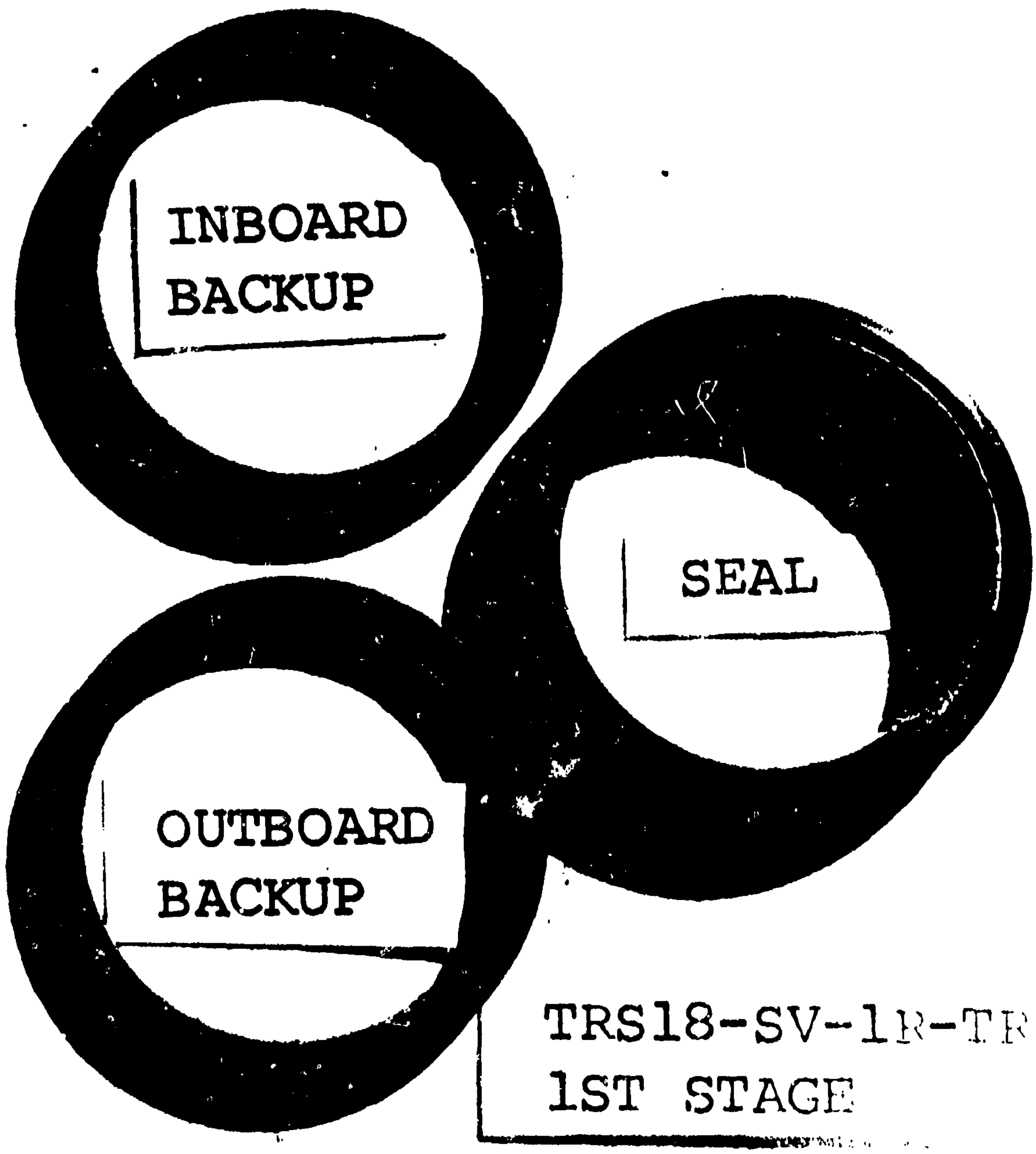


Figure 140. Candidate TRS18-SV (1st Stage) After Two Stage Rod Seal Screening Test.

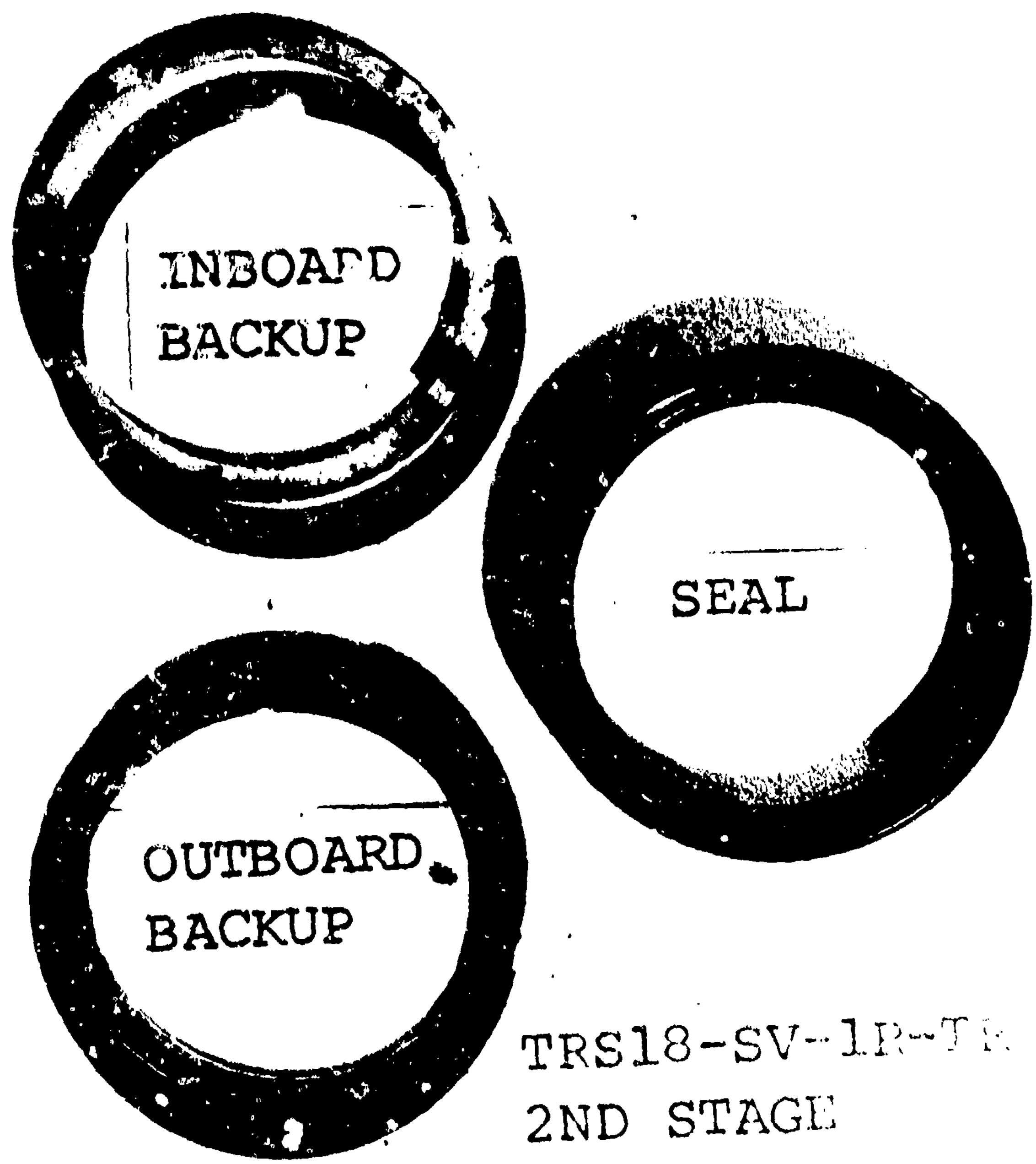


Figure 141. Candidate TRS18-SV (2nd Stage) After Two Stage Rod Seal Screening Test. "T" seal had very shallow axial wear pattern around ID.

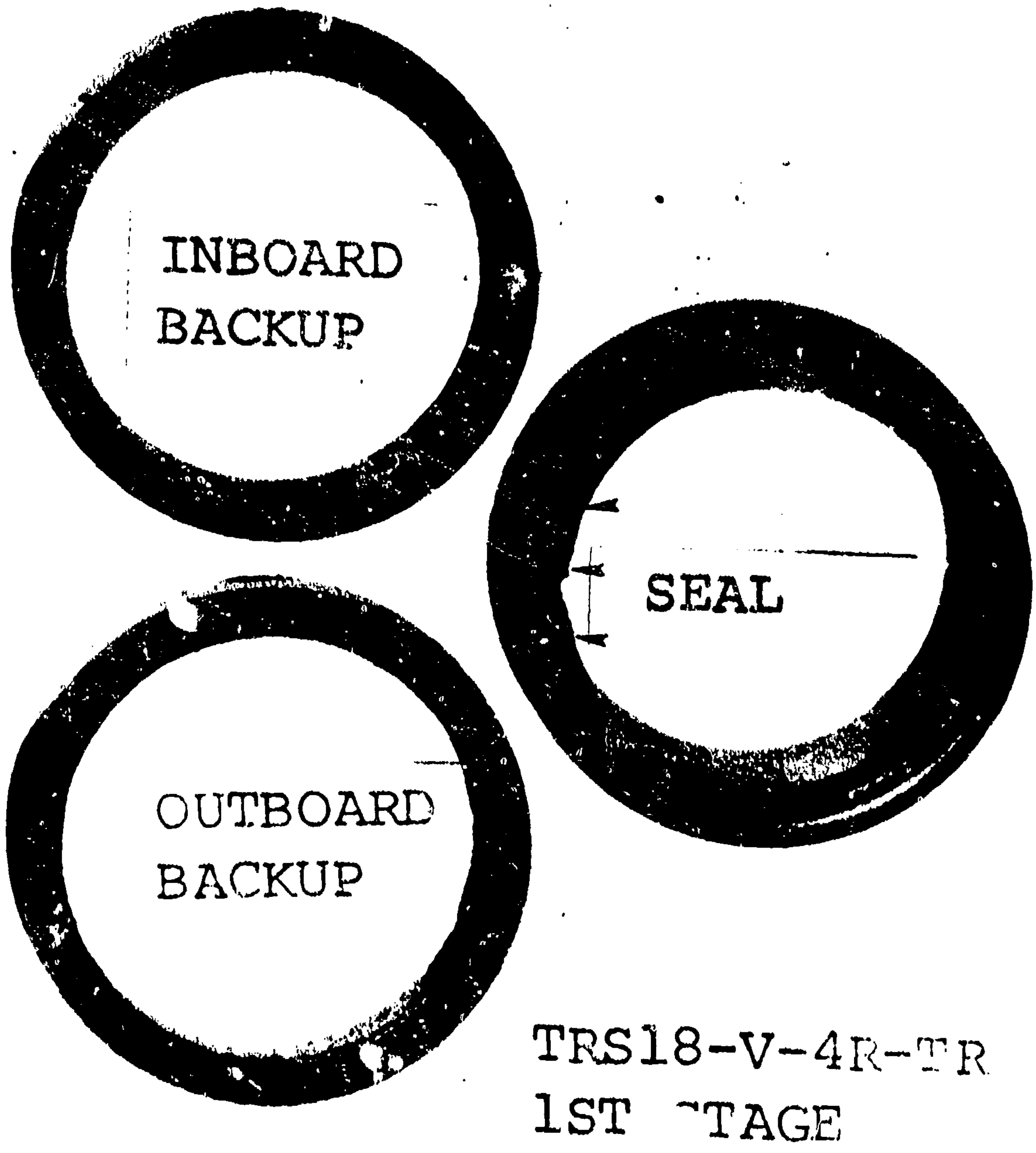


Figure 142. Candidate TRS18-V (1st Stage) After Two Stage Rod Seal Screening Test. Arrows denote area where seal was worn through.

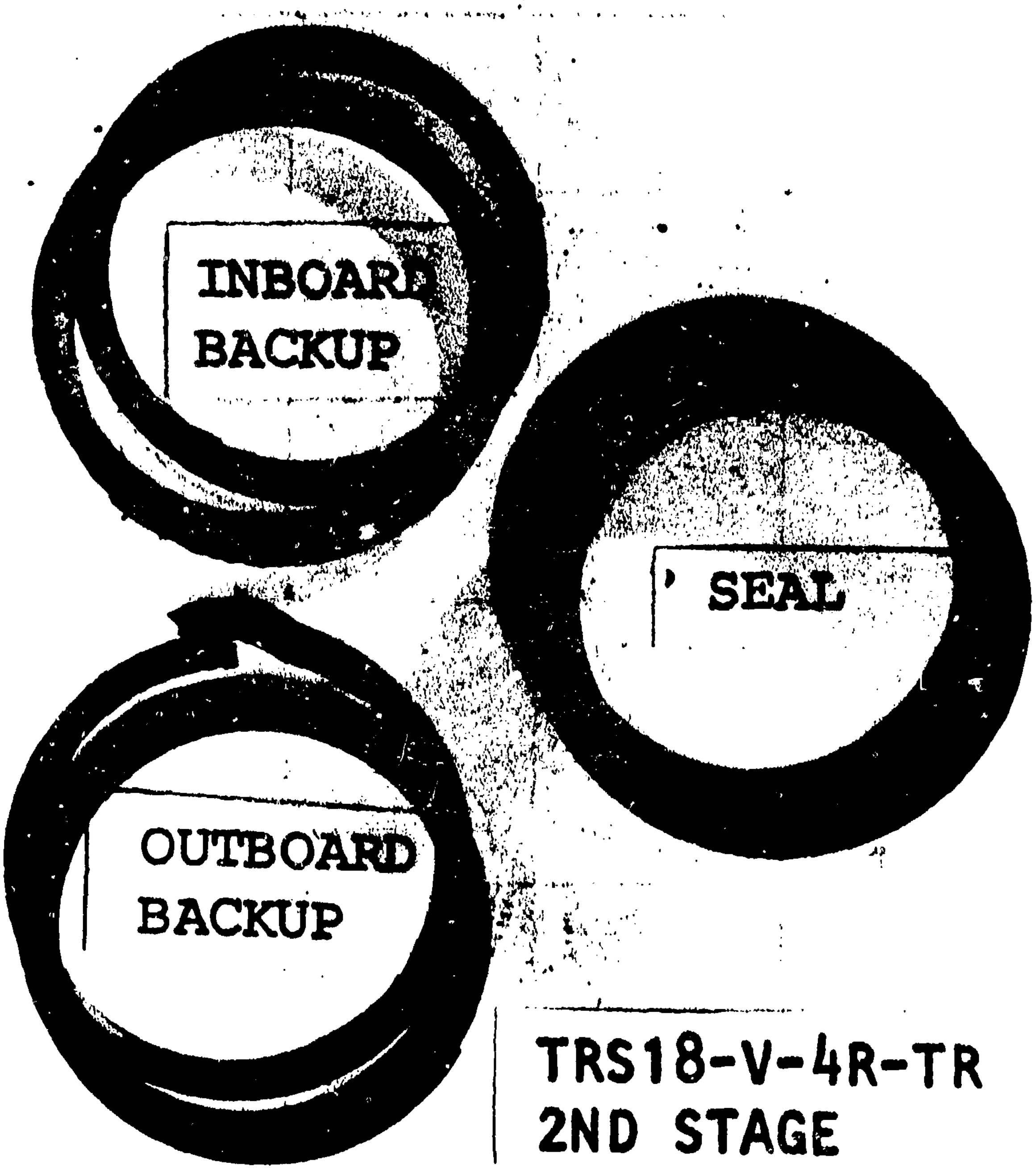


Figure 143. Candidate TRS18-V (2nd Stage) After Two Stage Rod Seal Screening Test. Arrow shows tip of the TFE backup which was displaced over the OD of the nylon outer backup.

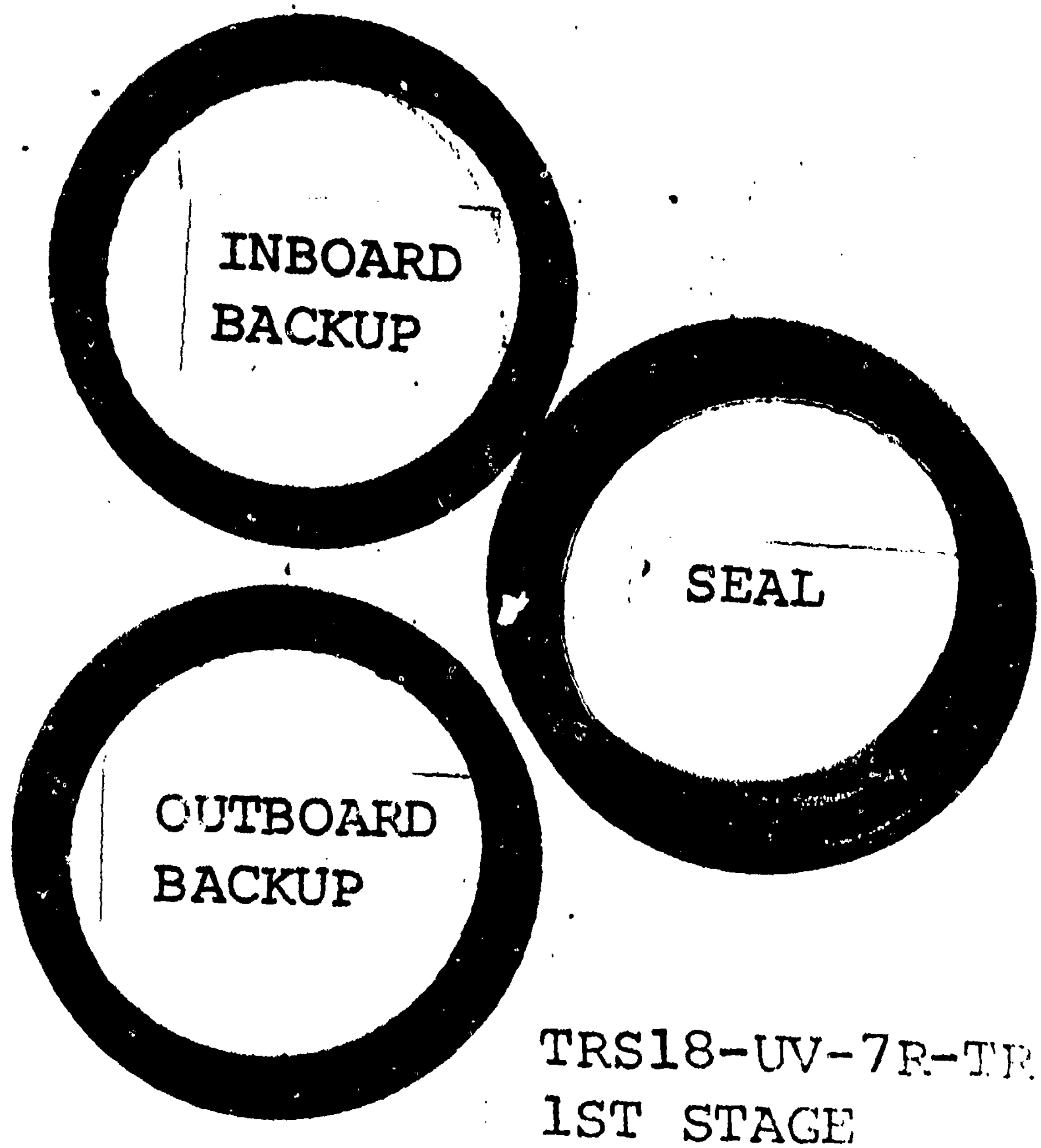


Figure 144. Candidate TRS18-UV (1st Stage) After Two Stage Rod Seal Screening Test. The cap seal is cracked around the ID and has began to separate.

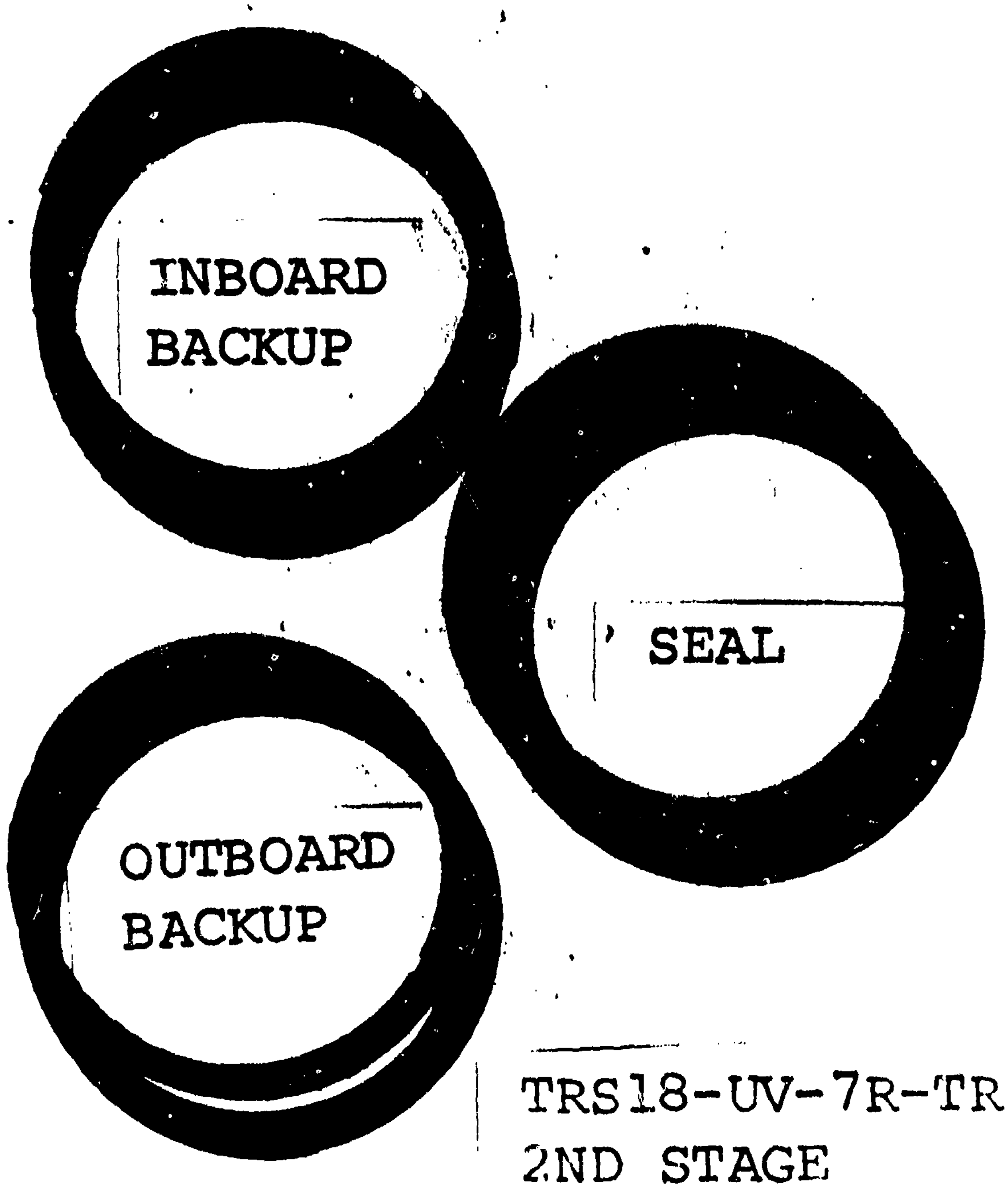


Figure 145. Candidate TRS18-UV (2nd Stage) After Two Stage Rod Seal Screening Test. Two stage installation had no external leakage.

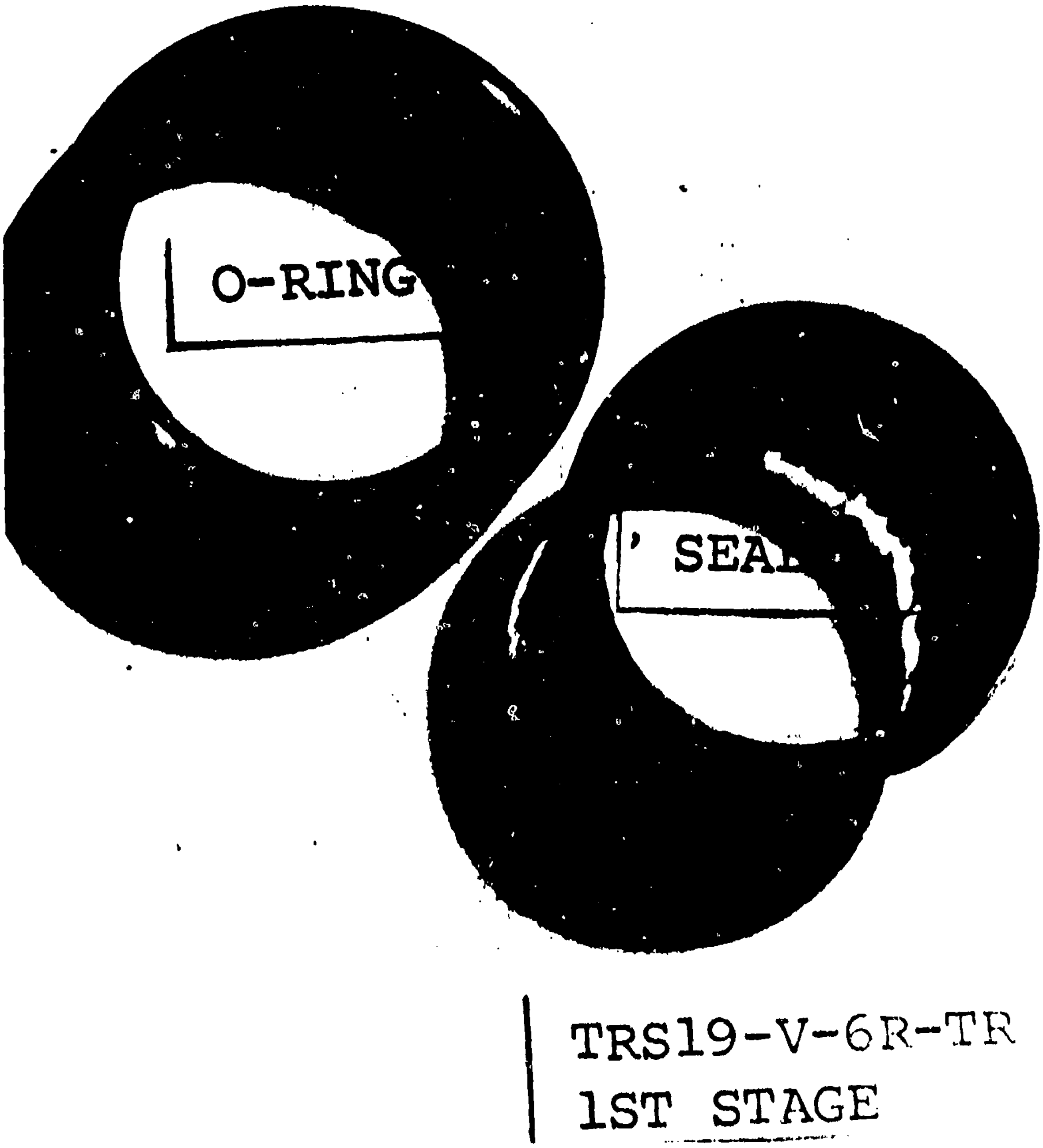


Figure 146. Candidate TRS19-V (1st Stage) After Two Stage Rod Seal Screening Test. Seal used -318 size O-ring to energize cap strip. This seal was worn through during test.

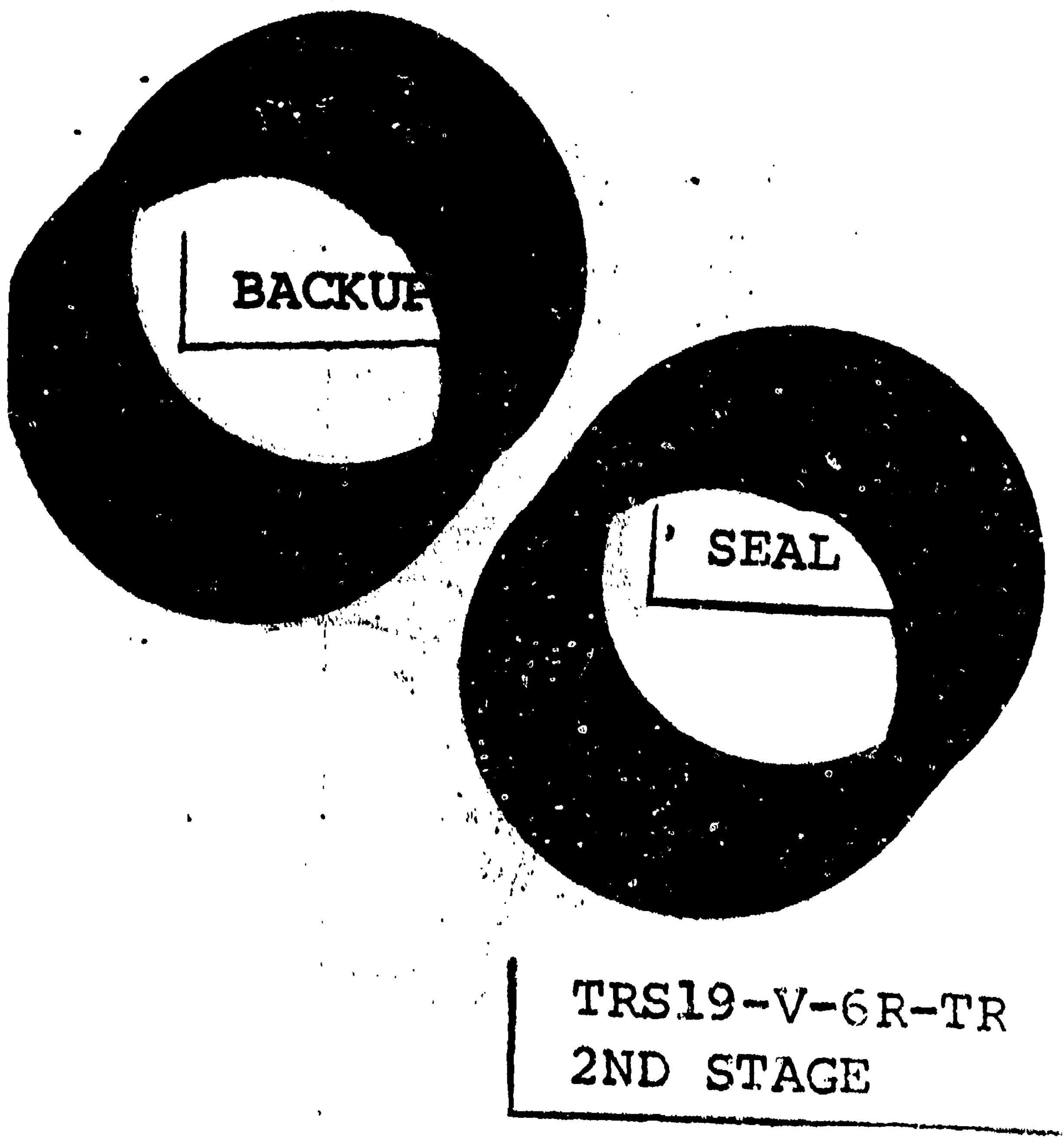


Figure 147. Candidate TRS19-V (2nd Stage) After Two Stage Rod Seal Screening Tests. Despite appearance of first stage, there was no external leakage of two stage installation.

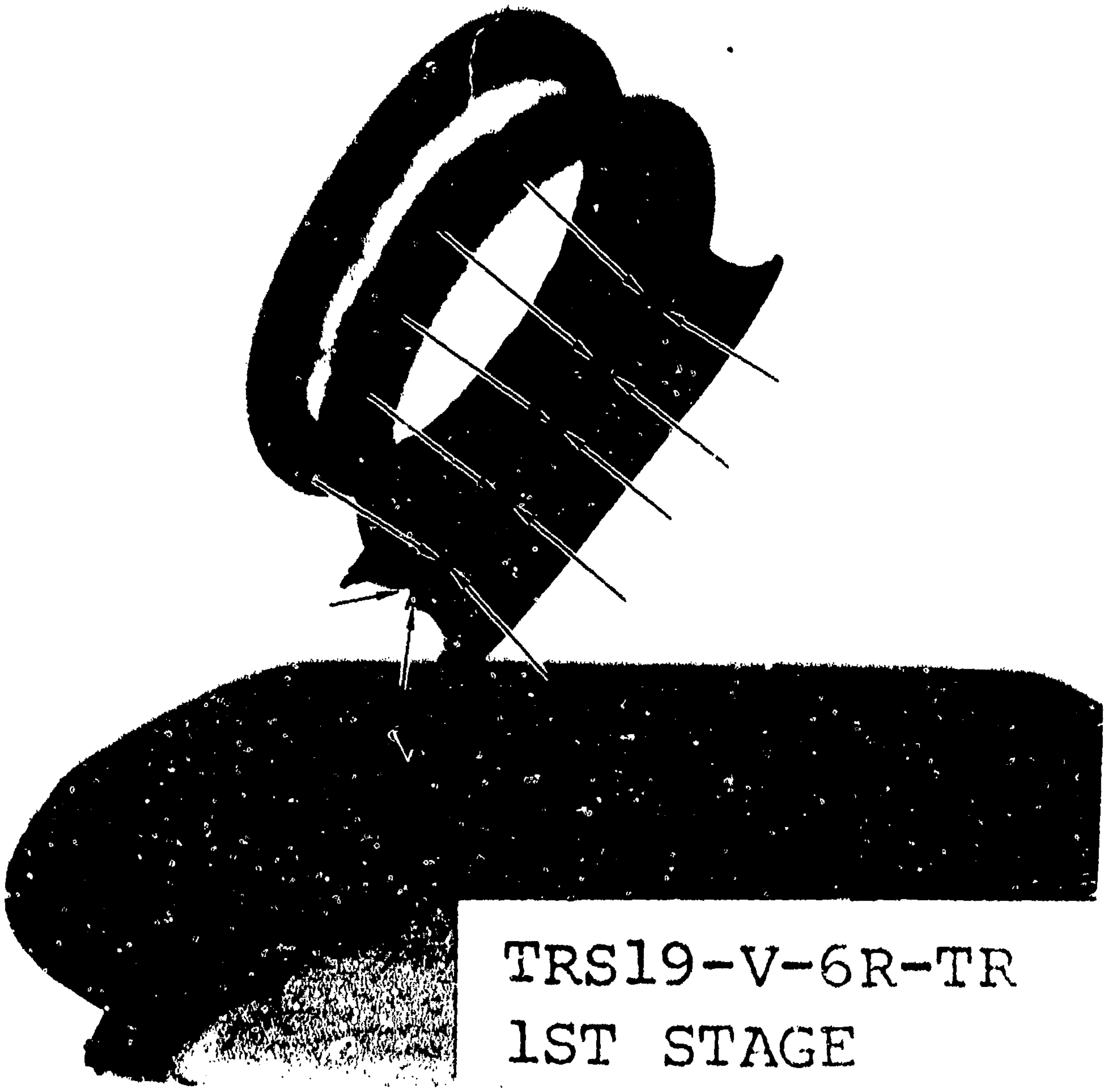


Figure 148. Another view of TRS19-V (1st Stage). Arrows show extent of seal damage.

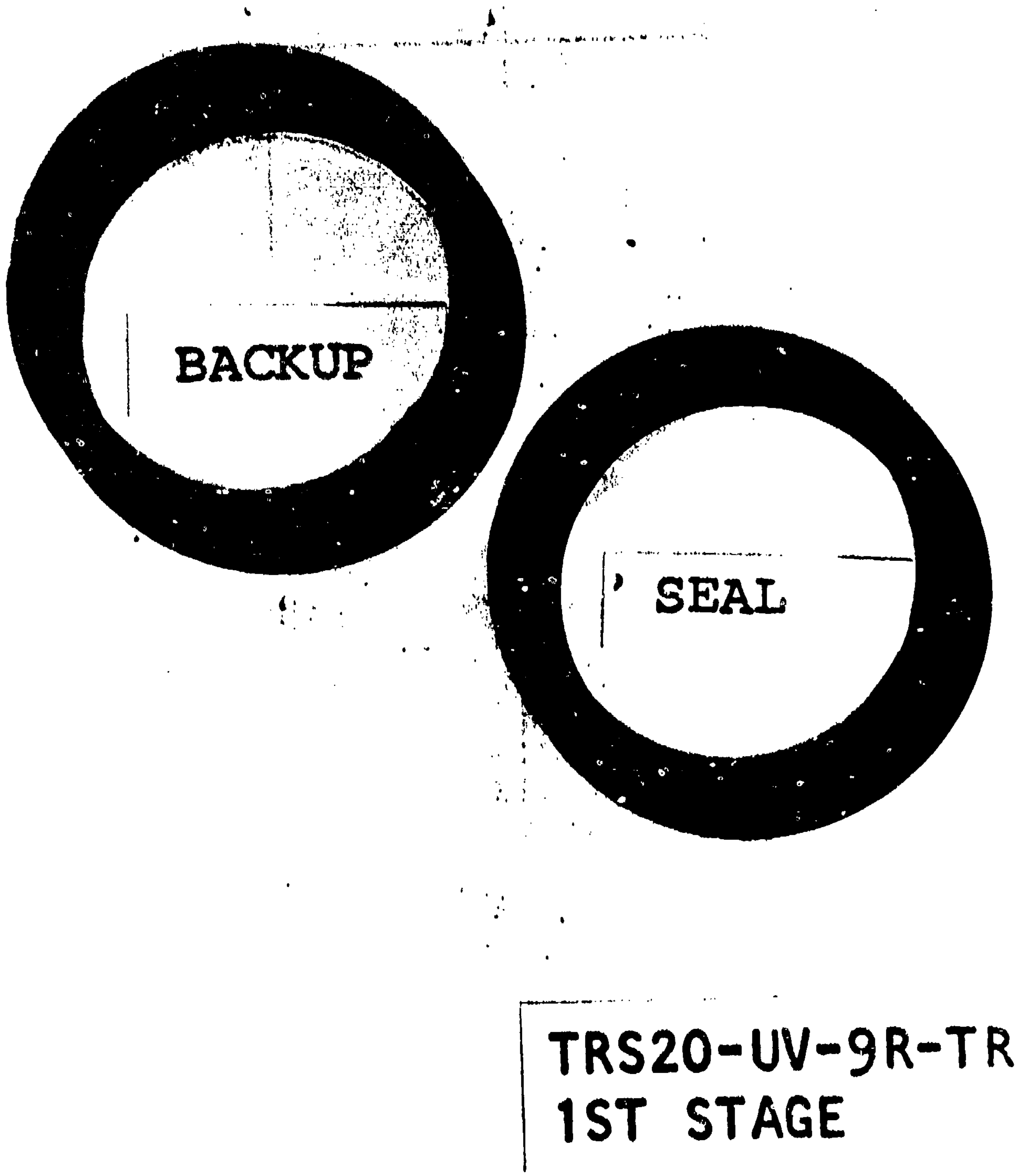


Figure 149. Candidate TRS20-UV (1st Stage) After Two Stage Rod Seal Screening Test. Seal was in excellent condition after test.

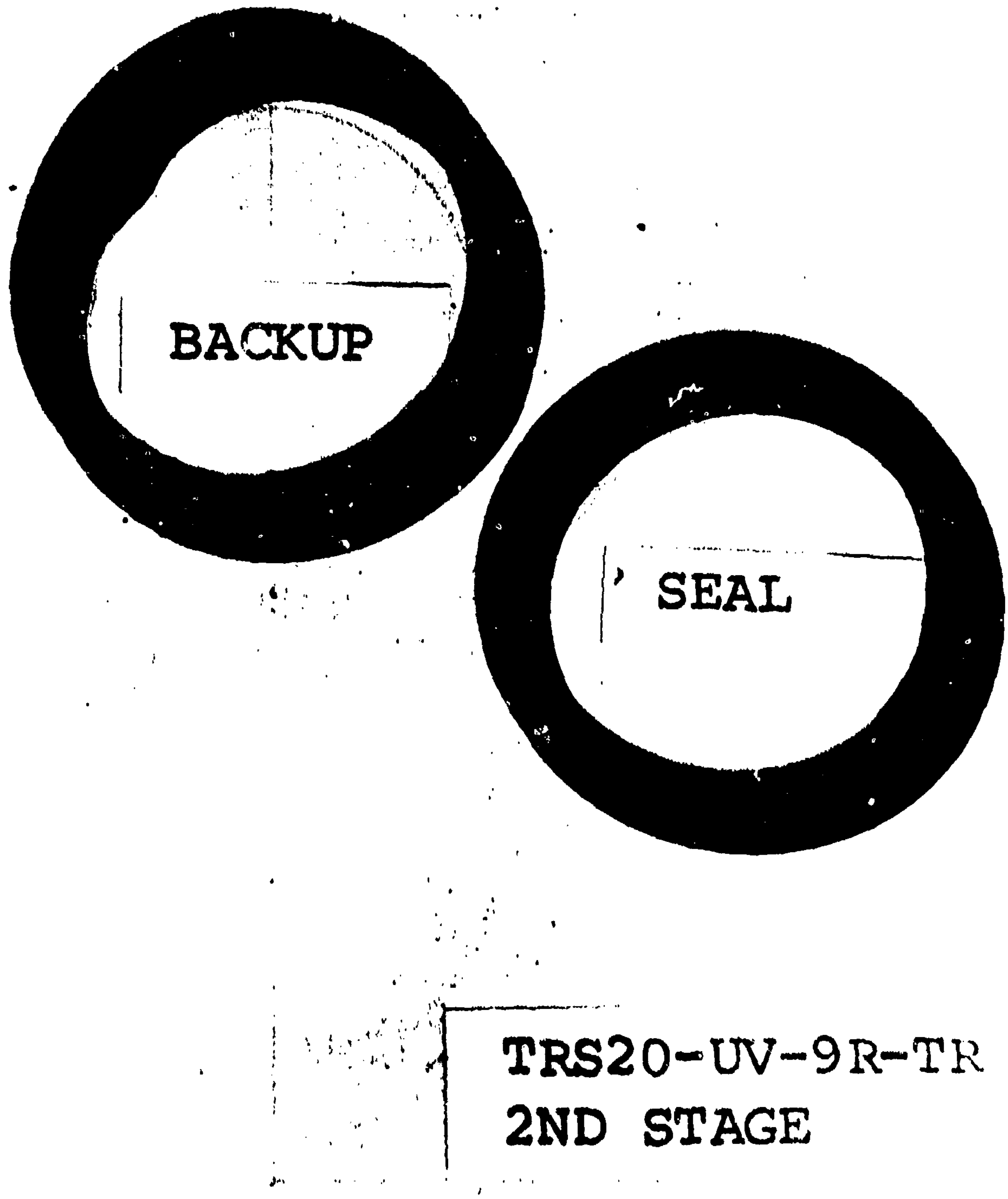


Figure 150. Candidate TRS20-UV (2nd Stage) After Two Stage Rod Seal Screening Test. No external leakage was observed with this two stage installation.

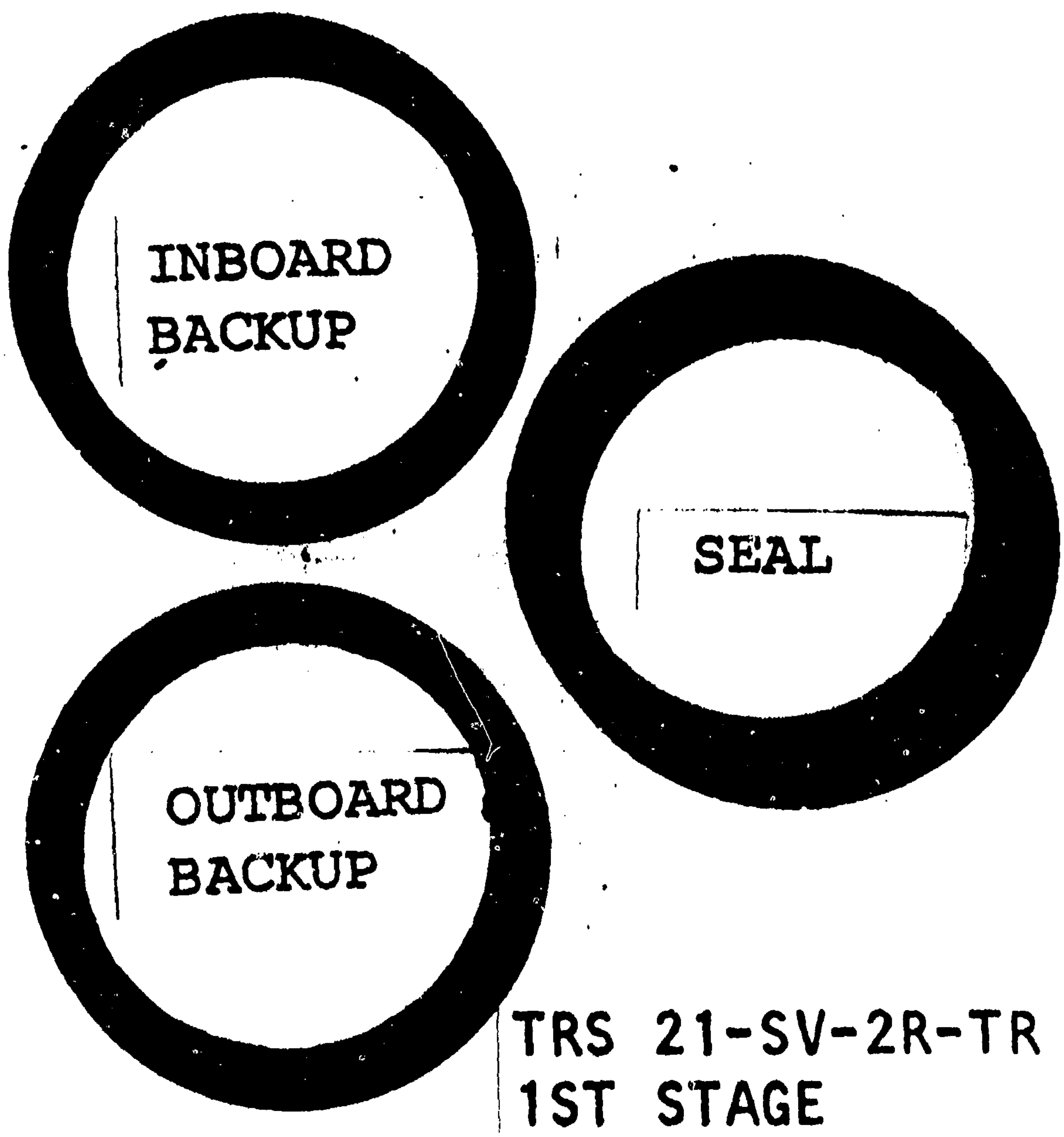


Figure 151. Candidate TRS21-SV (1st Stage) After Two Stage Rod Seal Screening Test. "Plus" seal and backups are Shamban Code 19.

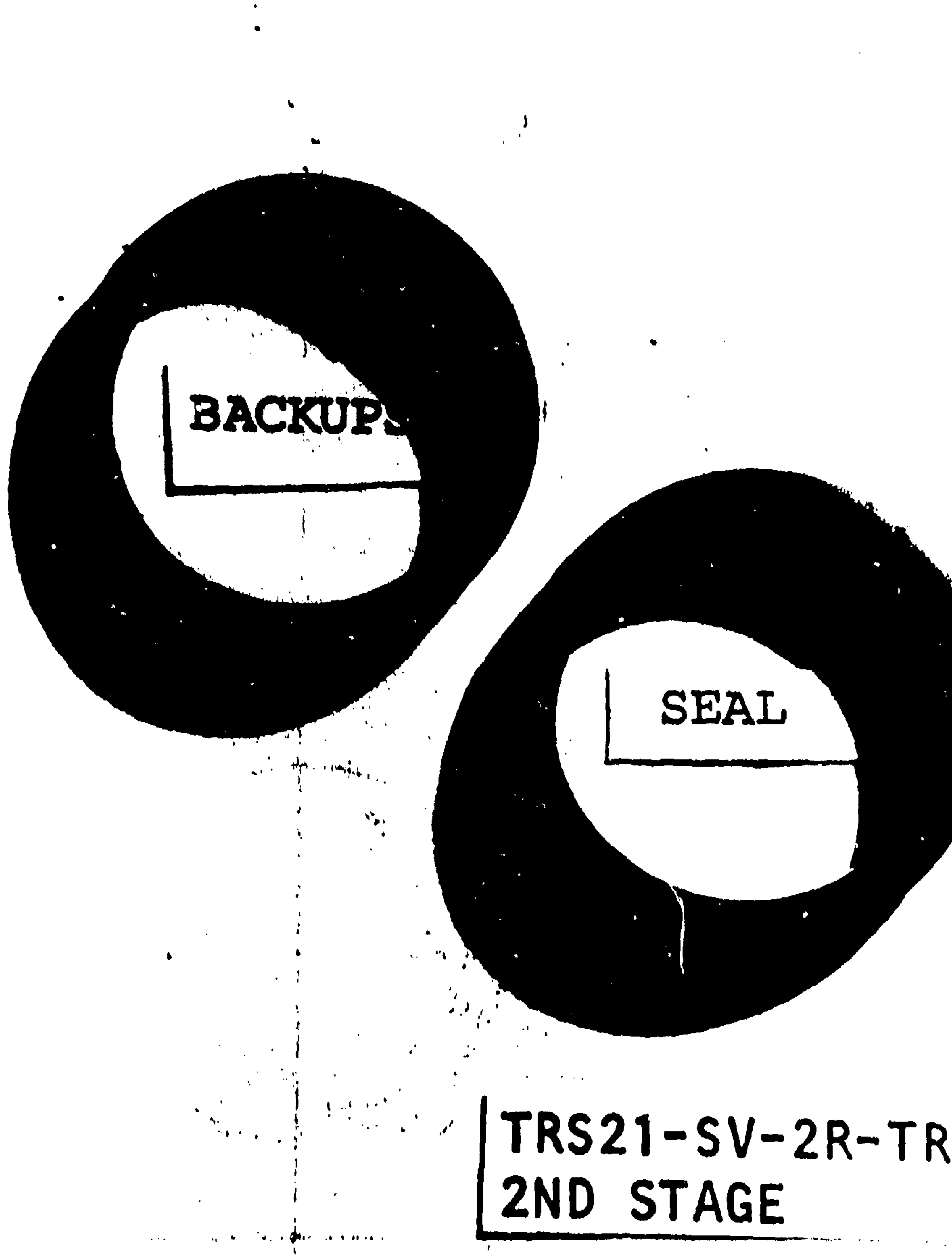


Figure 152. Candidate TRS21-SV (2nd Stage) After Two Stage Rod Seal Screening Test. Two stage backup and "Plus" seal are Shamban Code 19 material.

4. LONG LIFE TEST RESULTS

4.1 Objective:

The objective of the Long Life Tests was to evaluate the best performing candidates from the screening tests in a test equivalent in cycles to 5 years service in a fly-by-wire flight control system.. The number of endurance cycles completed was equivalent to 5 years service in a fly-by-wire horizontal tail flight control actuator.

4.2 Long Life Test Results Summary

Test Conditions - All candidates completed 13.31 x 10^6 cycles of the endurance spectrum which is equivalent to 5 years service in a high performance fighter aircraft with a fly-by-wire control system. Ambient temperature was 170/190°F in the insulated box. Oil temperature was 250/275°F when stabilized. Static leakage was collected with a 2 foot head of oil overnight and on weekends. Nine -65°F leakage tests were conducted. Dynamic leakage was collected over the entire test period.

Leakage - None of the four two stage candidates leaked. TRS 21-UV and TRS 6-UV had an oil film on the rod insufficient to form a drop.

Candidate B35 with the PNF O-ring was the only single stage seal which did not leak.

Using a static leakage criteria of 1 drop/12 hours for single stage seals, Candidate B35 had acceptable static leakage. B22, RS7, and B1 failed.

Using a low temperature leakage criteria of 2 drops/5 cycles, Candidate RS7 and two assemblies with Candidate B35 had acceptable low temperature leakage. One of the B3 candidates had the PNF O-ring. Backup candidates B22 and B1 failed.

Using a dynamic leakage criteria of 1.5 ml per block, all single stage candidates had acceptable dynamic leakage except the baseline, Candidate B1.

Rod Condition - The rods with Revonoc 18158 or unfilled Teflon seals (B22, B1, TRS4-UV, TRS6-UV) had little or no wear. The other rods with Shamban Compound 19 or Compound 99 have moderate to severe wear. The four most worn rods had axial abrasion sufficient to wear away the original 11 - 16 RMS grind marks. There appears to be no difference in rod wear with Compound 19 or 99.

Aluminum-Bronze End Cap - There is no improvement wear of rod with Aluminum-Bronze end cap compared to 17-4PH end caps with same plastic compound backup.

Scraper - None of the four S7 scrapers tested exhibited any visible wear or deformation. Rod wear was none to light. All had an interference fit with rod at room temperature after testing.

Seal Wear - Backup Candidate B35 in 17-4 PH end cap - no O-ring damage and little wear of backups.

Backup Candidate B22 - Little wear of backup, O-ring has light nibbling on ID.

Single Stage Candidate RS7 - No wear of seal.

Backup Candidate B35 in aluminum bronze end cap - The outboard backup is very worn with approximately 25 percent reduction in cross section. The ID is ≅ 1.005 inches. The O-ring has very light nibbling on the ID and is in fair condition.

Backup Candidate B35 with PNF O-ring - O-ring and backup in excellent condition.

Two Stage Candidate TRS21-UV - Both Plus seals in good condition.

Two Stage Candidate TRS4-UV - The inboard Trapezoid backup is very worn with approximately 25 percent reduction in cross section. The inboard Trapezoid elastomer had light nibbling around the ID. The inboard backup ID is ≈ 1.005 inches. The outboard seal is in excellent condition.

Two Stage Candidate TRS6-UV - The inboard seal O-ring has rolled and is abraded/nibbled over a large area. The inboard seal outboard backup ID > 1.005 inches and has worn approximately 6 percent on the cross section. The outboard seal O-ring has light nibbling around the ID on the outboard side. The redundant backups on the outboard seal were a loose fit on the rod.

Two Stage Candidate TRS20-UV - Neither the inboard or outboard hat seal has any wear or visible damage.

4.3 Derivation of Total Endurance Cycles for Long Life Test

The test spectrum derived for this program was used except that the 1, 2, and 10 percent strokes were superimposed upon the 50 percent (±1 inch) stroke. The number of cycles to be accomplished was derived as follows:

a. Contract F33615-78-C-2027 required the long life tests to be the equivalent of 5 years of aircraft life.

b. The derived spectrum of 40,000,000 cycles corresponds to 4000 hours of aircraft life. Therefore, cycles/flt hr = $40 \times 10^6/4000$ = 10000 cycles/flt. hr.

c. Aircraft usage data gives an average value of 264 flight hours per year for F-16 aircraft in peace time service.

d. Flight hour in five year equals 264 flt. hr/year x 5 year = 1320 flight hour/5 year.

e. Cycles in 5 years equals 1320 flight hours x 10000 cycles/flight hour = 13./2 x 10^6 cycles. Therefore, long life test requirement is 13.2 x 10^6 cycles.

f. The total number of cycles at each percent stroke was as follows:

1	1.1889 x 10^7
2	1.149 x 10^6
10	.829 x 10^5
50	.758 x 10^5
100	.330 x 10^4

4.4 Long Life Test Candidates

Selections were made from the backup ring, scraper, single stage rod seal, and two stage rod seal candidates. A comparison of a PNF elastomer O-ring was made with the M83461/1 O-rings used in all other backup ring tests. A comparison of aluminum bronze rod bushing material was made against 17-4PH material. All backup candidates were tested using M83461/1 material. Figure 153 shows the Long Life Test Candidates and Table 13 summarizes test results.

Backup Candidate B35 - Trapezoid shaped backup of a proprietary filler and MoS_2 filled Turcon. The configuration is identical to B3, B23, and B30 except for material. This candidate was tested with scraper candidate S7; was installed in the aluminum bronze end cap; and was tested with a PNF O-ring.

Backup Candidate B22 - Two-stage rectangular backup of Revonoc 18158 materials.

Single Stage Candidate RS-7 - "L" shaped backup and special/molded elastomer of M83461 compounds. Backup was Compound 99, a MoS_2 filled Turcon.

Scraper Candidate S7 - A very rigid design of acetal resin plastic.

Two Stage Rod Seal Candidate TRS 21-UV - This two stage candidate has a Shamban "Plus" seal inboard and outboard. The inboard seal was a single backup on each side. The outboard seal has a two stage backup on the outboard side.

Two Stage Rod Seal Candidate TRS4-UV - Both seals are the "trapezoid" seal. Backup material was Revonoc 18158. Elastomer was MIL-P-83461.

Two Stage Rod Seal Candidate TRS6-UV - Both seals are O-rings with Revonoc 18158 backups. The inboard seal has single backups on each side. The outboard seal has two stage backups.

Two Stage Rod Seal Candidate TRS20-UV - Both seals are the "Hat" seal in Shamban Compound 99, MoS_2 filled Turcon.

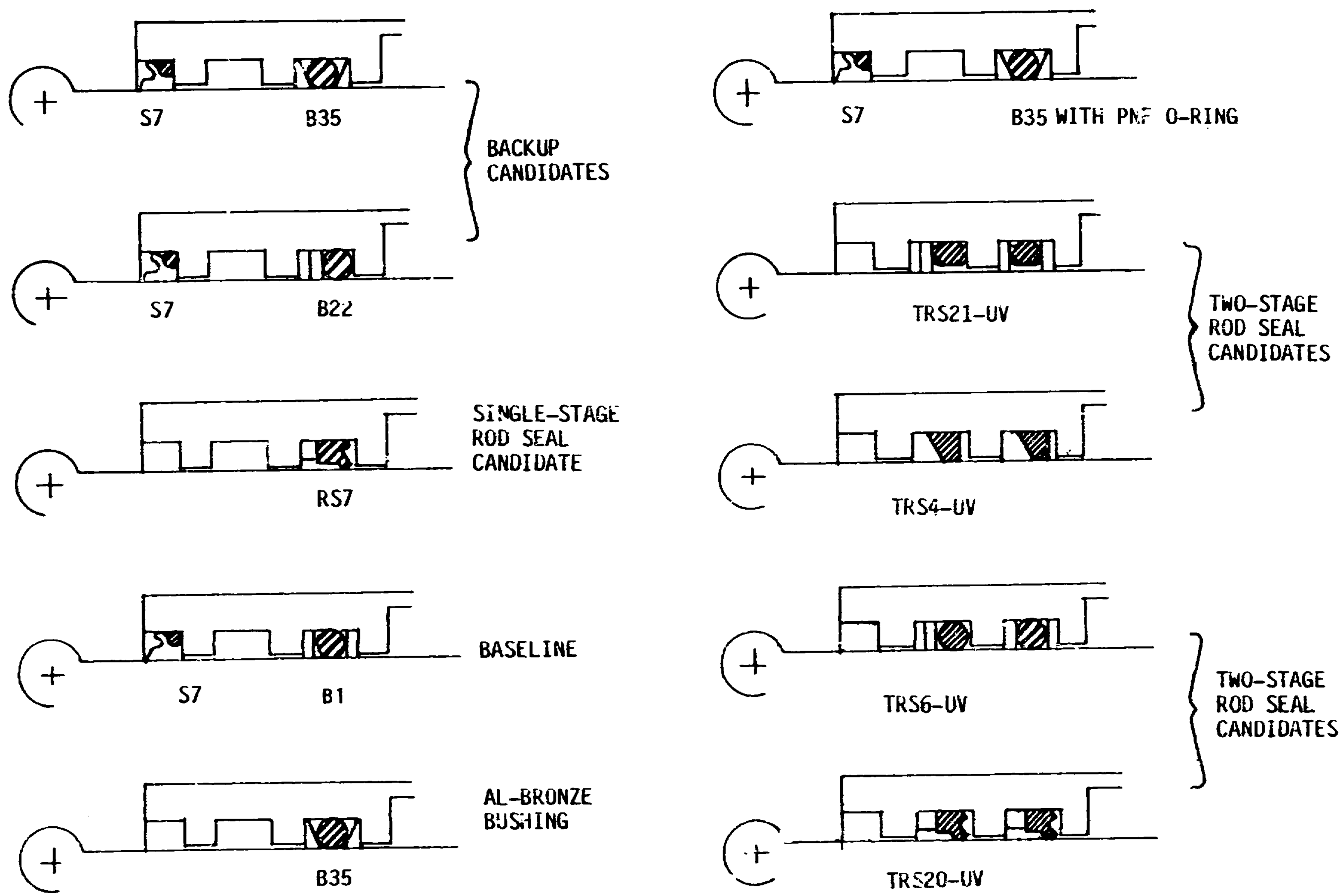


Figure 153. Long Life Test Candidates

TABLE 13. SUMMARY OF LONG LIFE TEST RESULTS

DYNAMIC SEALS FOR ADVANCED HYDRAULIC SYSTEMS

Total Cycles - 13.31 x 10^6

ASSY	CANDIDATE	Leakage [illegible] STATIC	-65	DYNAMIC	TOTAL
1	B35 (17-4 PH end cap)	0	1.95	6.0	7.95
2	B22	37.2	3.05	101.0	141.25
3	RS7	11.1	.1	7.35	18.55
4	B1 (baseline)	30.15	.05	187.0	217.2
5	B35 (al-bronze end cap)	.05	0	2.4	2.45
6	B35 (PNF O-ring)	0	0	0	0
7	TRS21-UV	0	0	0	0
8	TRS4-UV	0	0	0	0
9	TRS4-UV	0	0	0	0
10	TRS20-UV	0	0	0	0

4.5 Test Results

Candidate B1 - MS28774-214

See Figure 154. The outboard backup is nearly worn thru in two locations. The O-ring shows very light nibbling on the ID and would be classified as good condition. The rod has minimal wear and exhibits only one very small mark which is deeper than the original 12-16 RMS finish. Leakage was 30.15 ml static, .05 ml low temperature, and 187 ml dynamic. Diametral clearance was .0030.

Candidate B22; CEC4862-214NC; C. E. Conover Co.

See Figure 155. The two stage backup cross section was worn to .10 at one location versus .121 for a new backup. The O-ring had very little nibbling on the ID and would be classified as good. There is no appreciable wear of the rod. Leakage recorded was 37.2 ml static; 3.05 ml low temperature, and 25 ml dynamic. Diametral clearance was .0027.

Candidate B35; S32975-214-19; W. S. Shamban.

See Figure 156. No damage occurred to the O-ring. The ID of both backups conformed to the rod diameter of .998 inches. The cross section of the outboard backup was .1097 versus .108 minimum for a new backup. Wear on rod is greatest where both the seal and scraper 1 and 2 percent strokes occurred. Depth of wear is sufficient to obliterate 12-15 RMS finish marks. In areas where only the rod or the scraper passed, wear is low to moderate. Leakage was 0 static, 1.95 ml low temperature, and 6.0 ml dynamic. Diametral clearance was .0030.

Candidate B35 in Aluminum Bronze Bushing

See Figure 157. The outobard backup is very worn. The ID of the outboard backup is ≅ 1.004. The cross section of outboard backup averaged .084 versus .108 min for a new backup. The O-ring had very light nibbling on the ID. Rod is worn in area exposed to 1-2 percent stroke sufficiently to remove original 12-15 RMS grind marks. Wear of chrome is approximately .0002 on the diameter in the most worn area. Leakage was .05 ml static, 0 low temperature, and 2.4 ml dynamic. Diametral clearance was .0030.

Candidate B35 with PNF O-Ring

See Figure 158. The PNF O-ring is undamaged. The backups have minimal wear. The rod has a very small area approximately .62 x .25 where wear has removed the 12 to 15 RMS grind marks on the chrome. There is no measurable difference between original and current rod diameter. No leakage was recorded for the static, low temperature, or dynamic conditions. Diametral clearance was .0029.

Candidate RS7; S33050-214P-99; W. S. Shamban

See Figure 159. There is no evidence of nibbling or any damage to the elastomer. The ID of the plastic portion of the seal conforms to the rod diameter of .9976. Some discoloration of the chrome occurred due to the MoS_2 filler in the seal. Leakage for Candidate RS7 was 11.1 ml static, .1 ml low temperature, and 7.35 ml dynamic.

Candidate TRS4-UV; CEC5056-214; C. E. Conover Co.

Inboard Seal. See Figure 160. The trapezoid backup is very worn with a reduced cross section averaging .083 inches versus .109 min for a new backup. The ID is a loose fit on a 1.005 diameter plug gage. The elastomer fits on a .982 diameter plug gage and exhibits a uniform light nibbling or fretting around the ID next to the backup.

Outboard Seal. See Figure 161. The backup cross section is .1175 with an ID = .9977. The elastomer has no evidence of use.

The rod is in excellent condition. The only evidence of use is a number of very light burnished marks running axially which are about equal in depth to the original 13 -14 RMS grind marks. Leakage was zero for the static, low temperature and dynamic conditions.

Candidate TRS6-UV; CEC4981-214; C. E. Conover Co.

Inboard Seal. See Figure 162. The inboard backup is extruded toward the cylinder indicating pressure between seals. The O-ring has rolled and shows much fretting and nibbling over much of the outboard side. The outboard backup ID is loose fit on a 1.0042 diameter plug gage. Cross section of outer backup is .1101 versus .118 minimum for a new backup.

Outboard Seal. See Figure 163. The O-ring has light nibbling around the ID on the outboard side. It did not roll. The outboard backup ID is a loose fit on a .9977 diameter plug gage. The inboard backup is a loose fit on a 1.0042 diameter plug gage. Cross section is .1199. The rod is in excellent condition. Only a slight discoloration in wear areas with very light axial marks indicate the rod is used. Leakage was zero for the static, low temperature and dynamic conditions.

Candidate TRS20-UV; S33050-214P-99; W. S. Shamban Co.

See Figures 164 and 165. The inboard and outboard seals were in excellent shape upon conclusion of testing. The elastomers exhibited no wear or damage. The rod has a uniform pattern of axial wear marks that are deeper than the .12 to 15 RMS grind marks on unworn portions of the rod. No leakage was recorded for the static, low temperature, or dynamic conditions.

Candidate TRS21-UV; S33157-214-19; W. S. Shamban

See Figures 166 and 167. The inboard and outboard seals still have an interference fit with the rod. The seals shows no effect from the test. Leakage was zero for static, low temperature, and dynamic conditions. The rod has an area 1.87 x .38 of wear which has removed the original 12-16 RMS grind marks. There are seven distinct graduations in wear/discoloration of the rod. Beginning at the piston for 1.75 inches is an area of no wear. From 1.75 inches to 2.65 inches the chrome is slightly darker in the area contacted during the 10 to 100 percent cycles. From 2.65 to 3.8 inches is an area contacted by both seals for 1 - 2 percent cycles on inboard seal and 10 - 100 percent on outboard. From 3.8 to 4.65 is an area contacted by both seals for all cycles. From 4.65 to 5.8 is an area contacted by the inboard seal on 10 - 100 percent cycles and the outboard seal on 1 - 2 per cent cycles. 5.8 inches to 6.7 is contacted by the outboard seal on 10 - 100 percent cycles. Greater than 6.7 inches was contacted by the wiper only.

Candidate S7; 120-218-1709; Dowty Ltd.

This scraper candidate was installed to evaluate rod wear on four of the seal test assemblies. Upon conclusion of tests, none of the four samples exhibited any wear or damage. Rod wear was not increased by the addition of a scraper. See Figure 168 for typical appearance of scrapers following test.

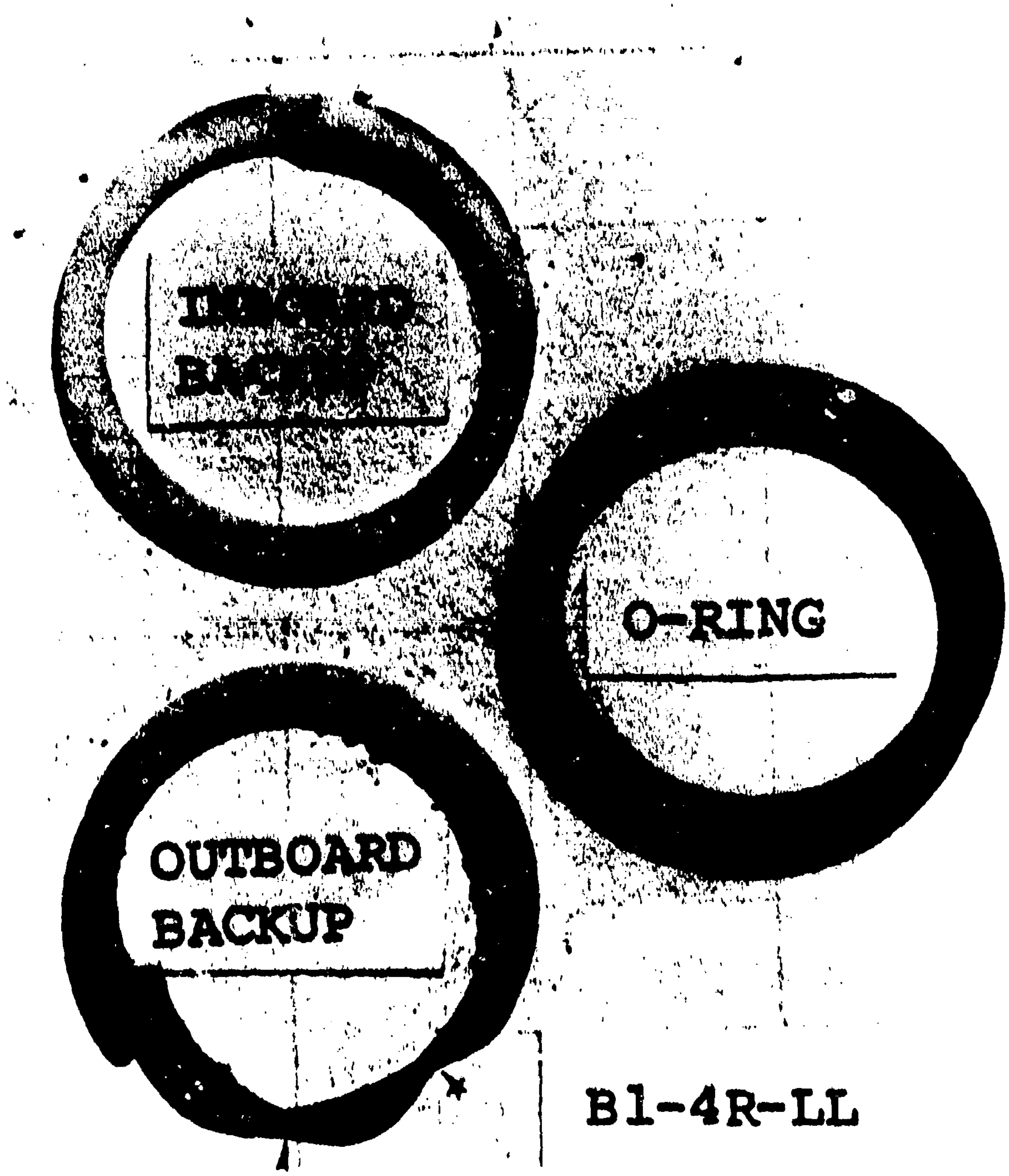


Figure 154. Candidate B1 After Long Life Test. Note severely worn areas on backup. O-ring is in good condition.

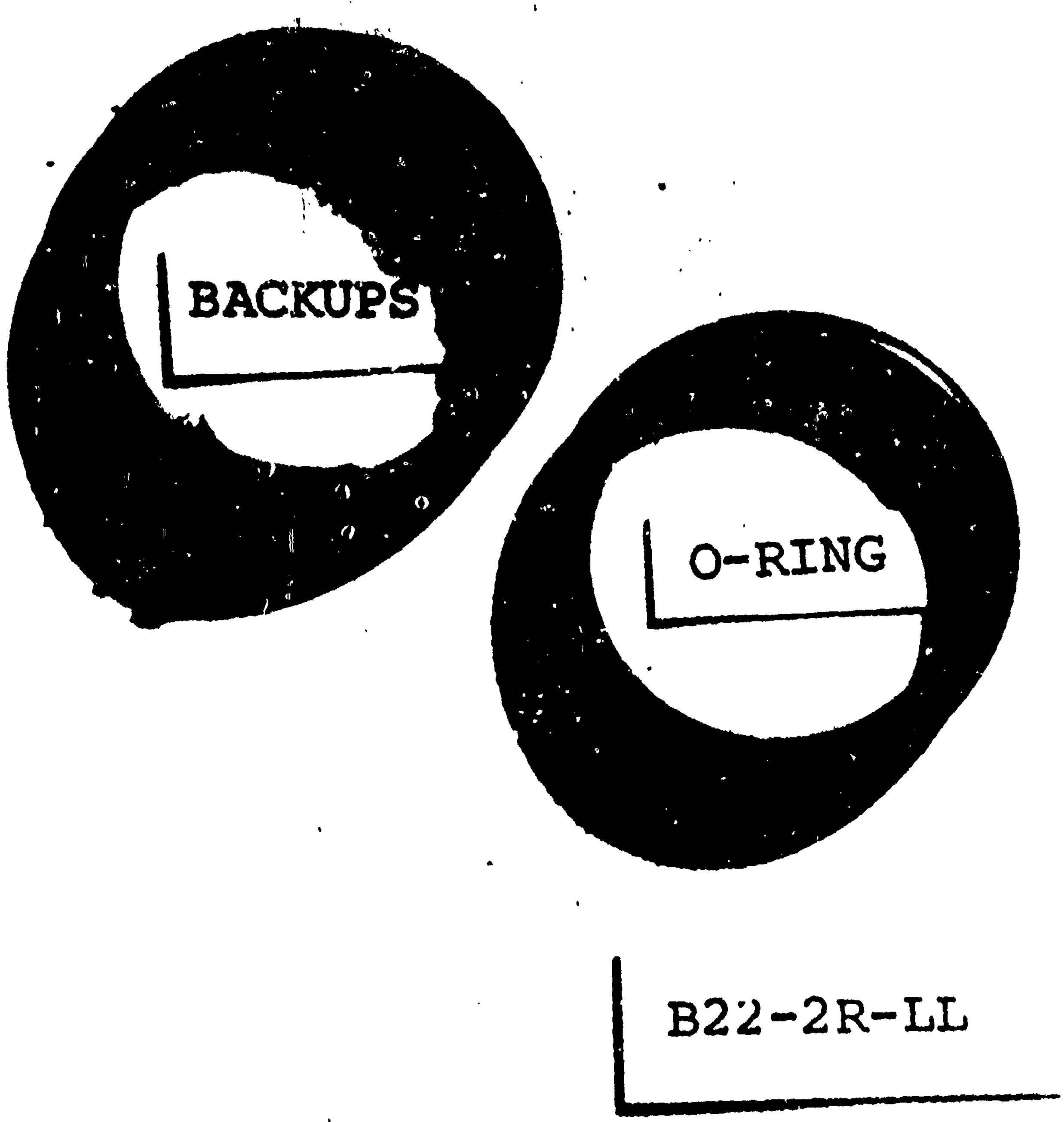


Figure 155. Candidate B22 After Long Life Test. O-ring is in good condition.

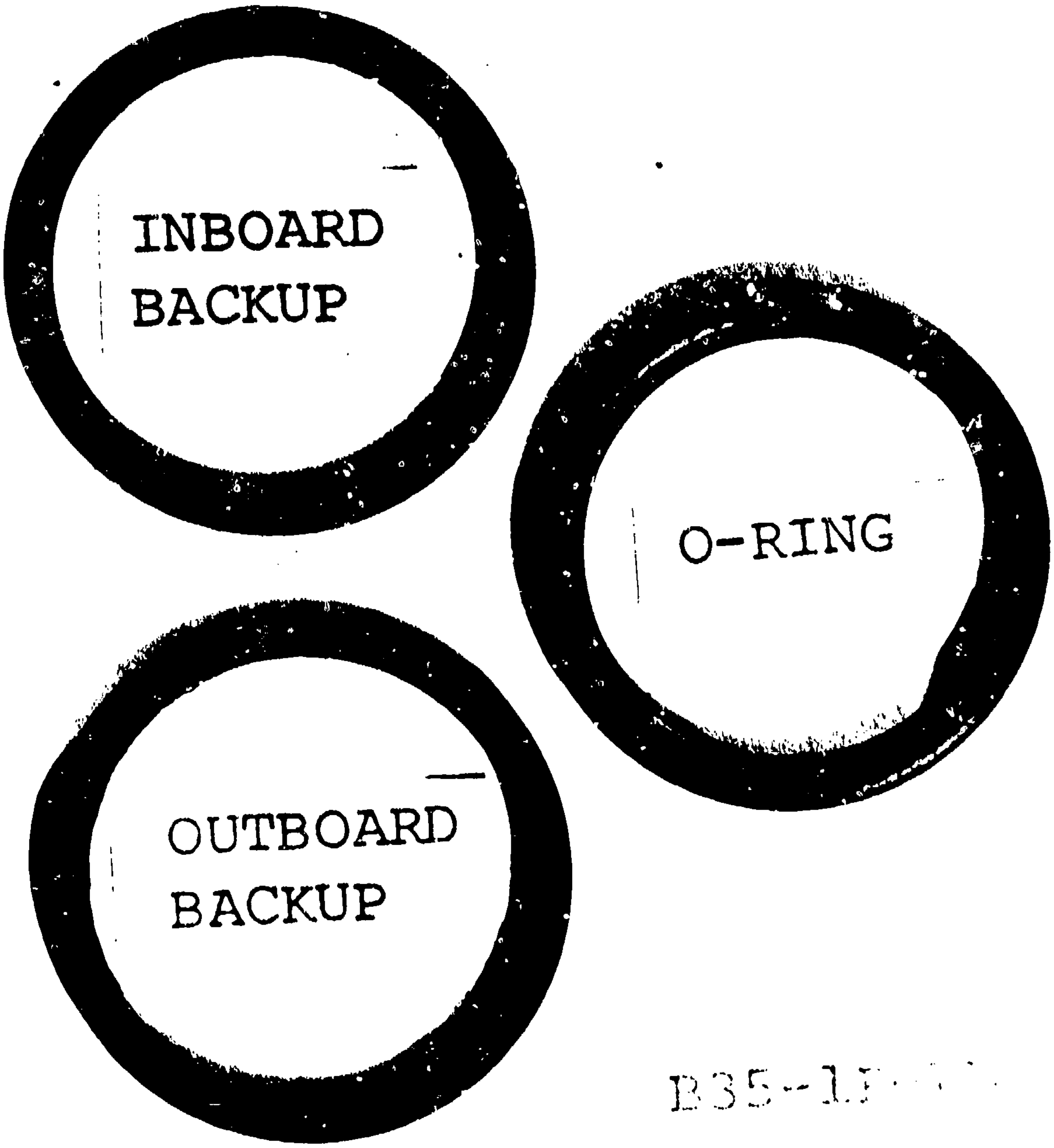


Figure 156. Candidate B35 After Long Life Test. O-ring is in excellent condition after 13.31 x 10^6 endurance cycles.

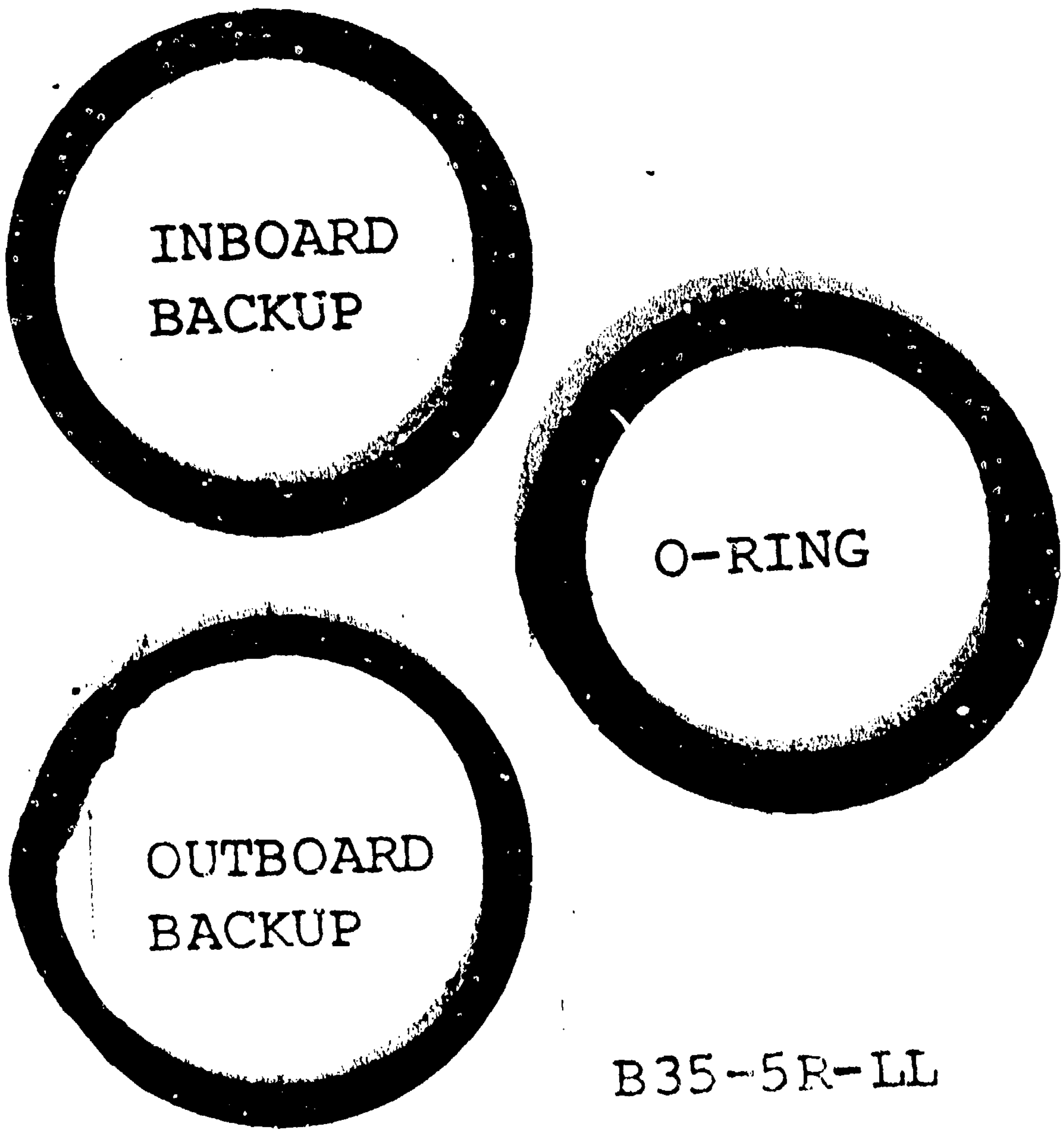


Figure 157. Candidate B35 After Long Life Test - Aluminum Bronze End Cap Installation. O-ring is in good condition. The outboard backup ID was loose fit on rod after tests.

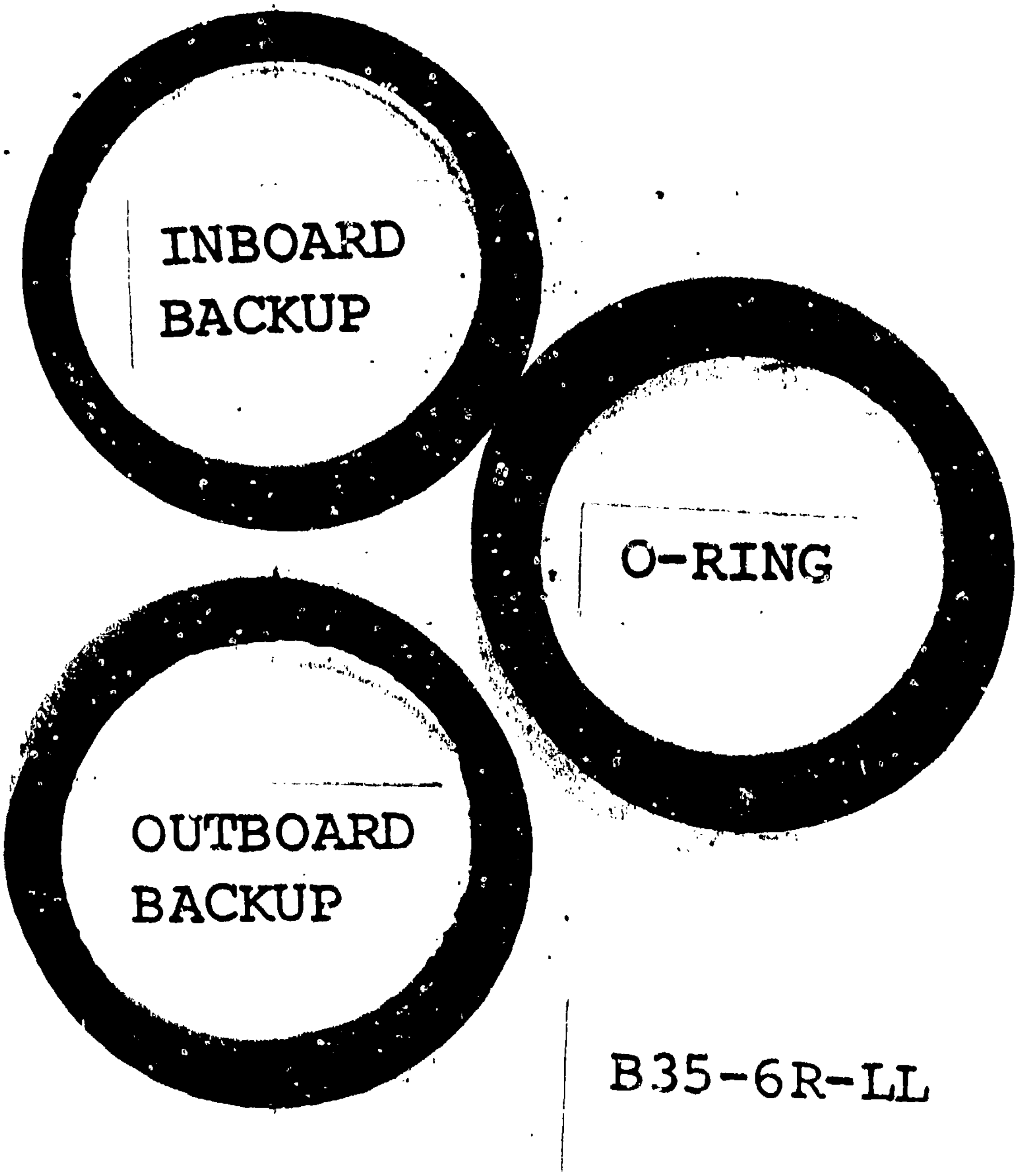


Figure 158. Candidate B35 After Long Life Test - With PNF O-Ring. O-ring is PNF material and is in excellent condition. Seal had zero leakage in 13.31 x 10^6 endurance cycles.

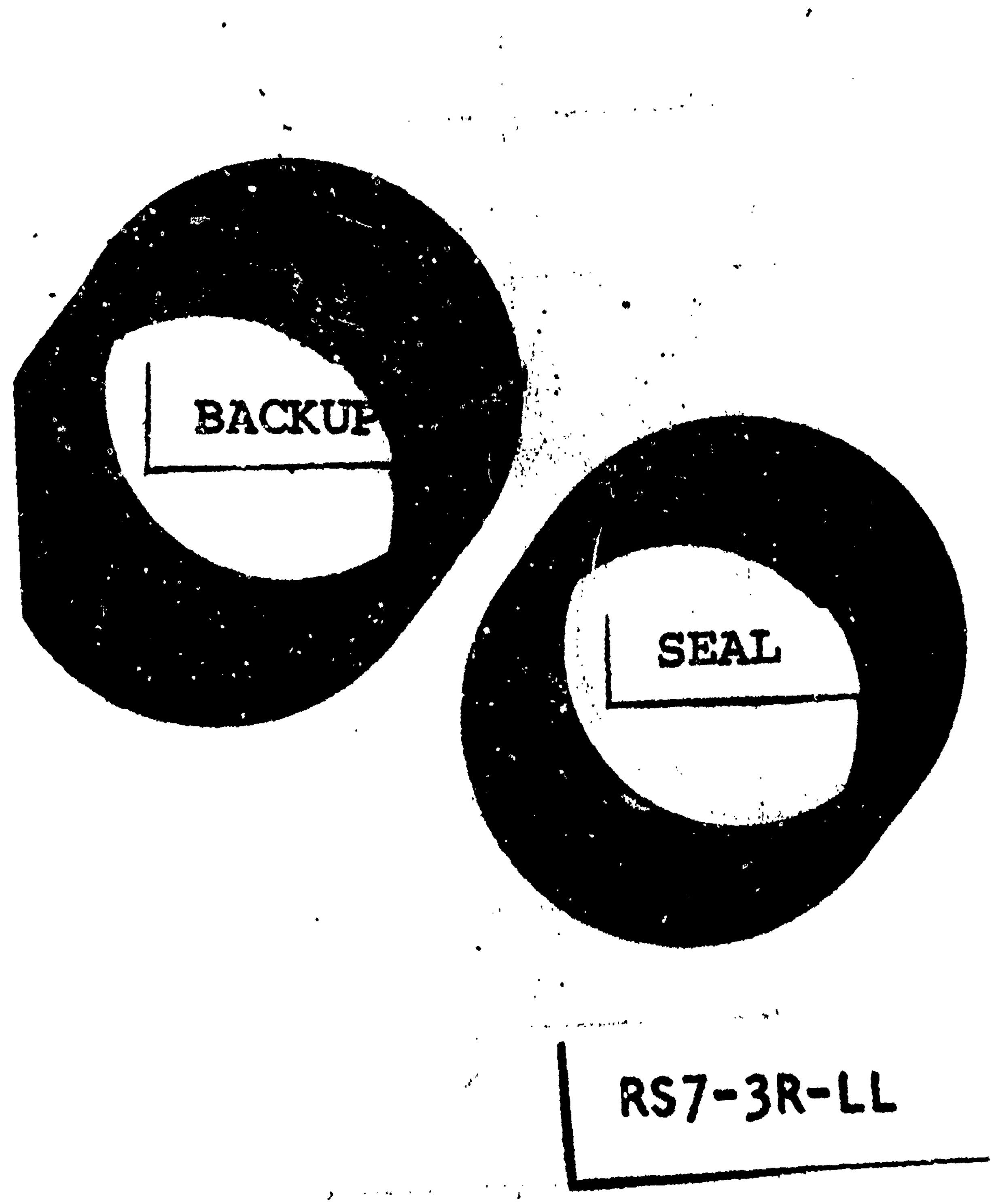


Figure 159. Candidate RS7 After Long Life Test. Seal and backup are in excellent condition.

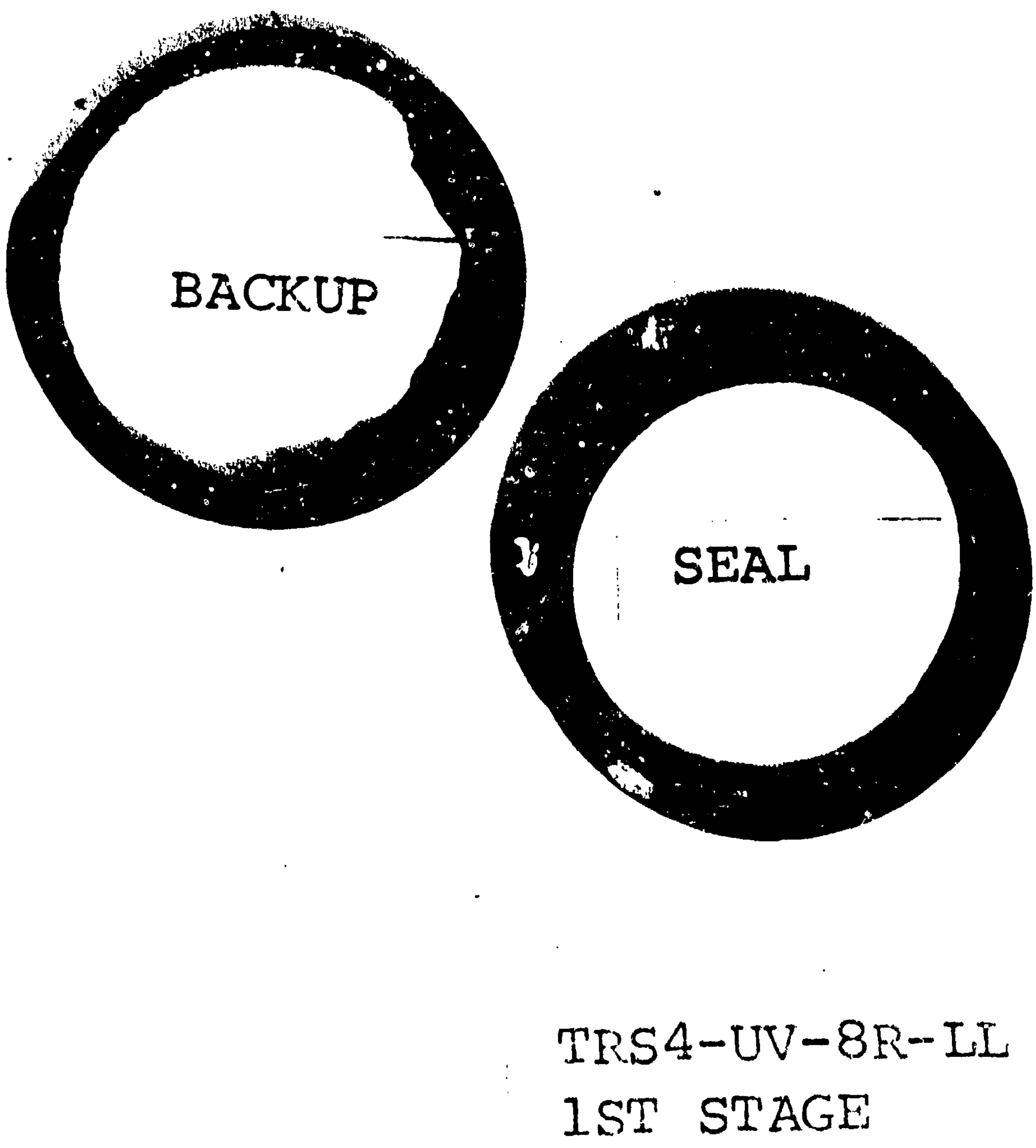


Figure 160. Candidate TRS4-UV (1st Stage) After Long Life Test. The backup cross section has worn approximately 25 percent and the ID is greater than 1.005 inch.

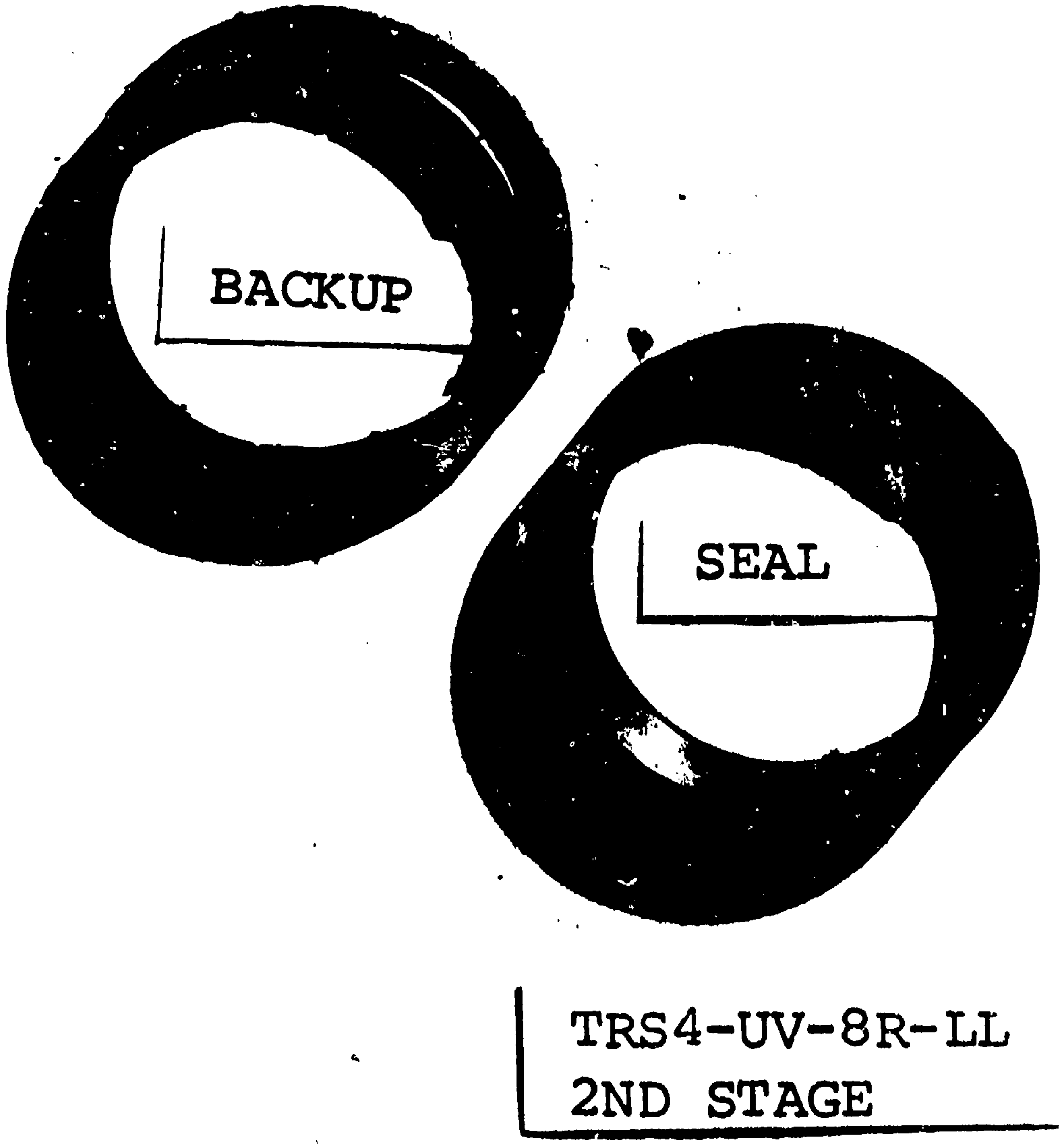


Figure 161. Candidate TRS4-UV (2nd Stage) After Long Life Test. The seal and backup are in excellent condition. Zero leakage was recorded.

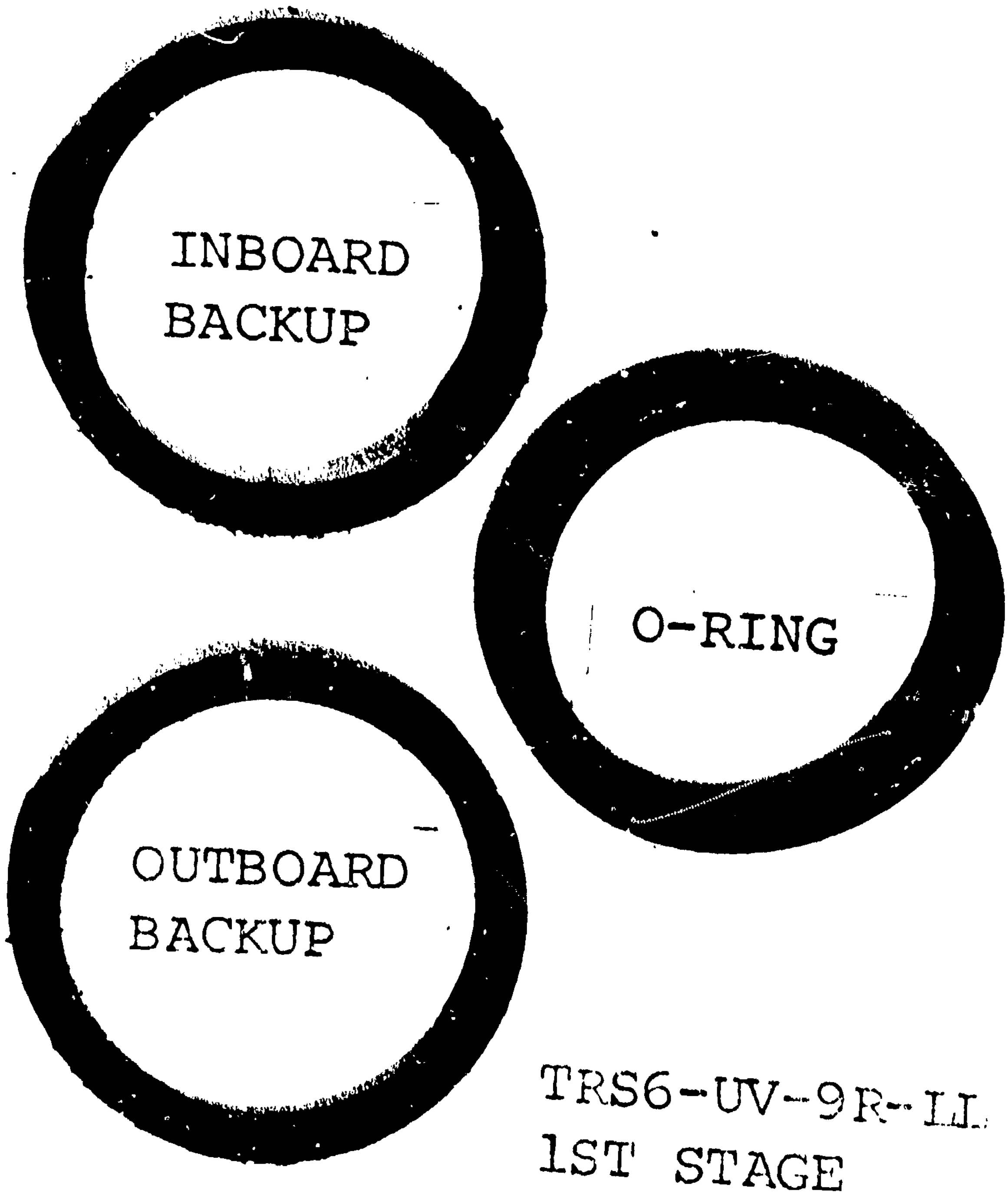


Figure 162. Candidate TRS6-UV (1st Stage) After Long Life Test. O-ring is in poor condition.

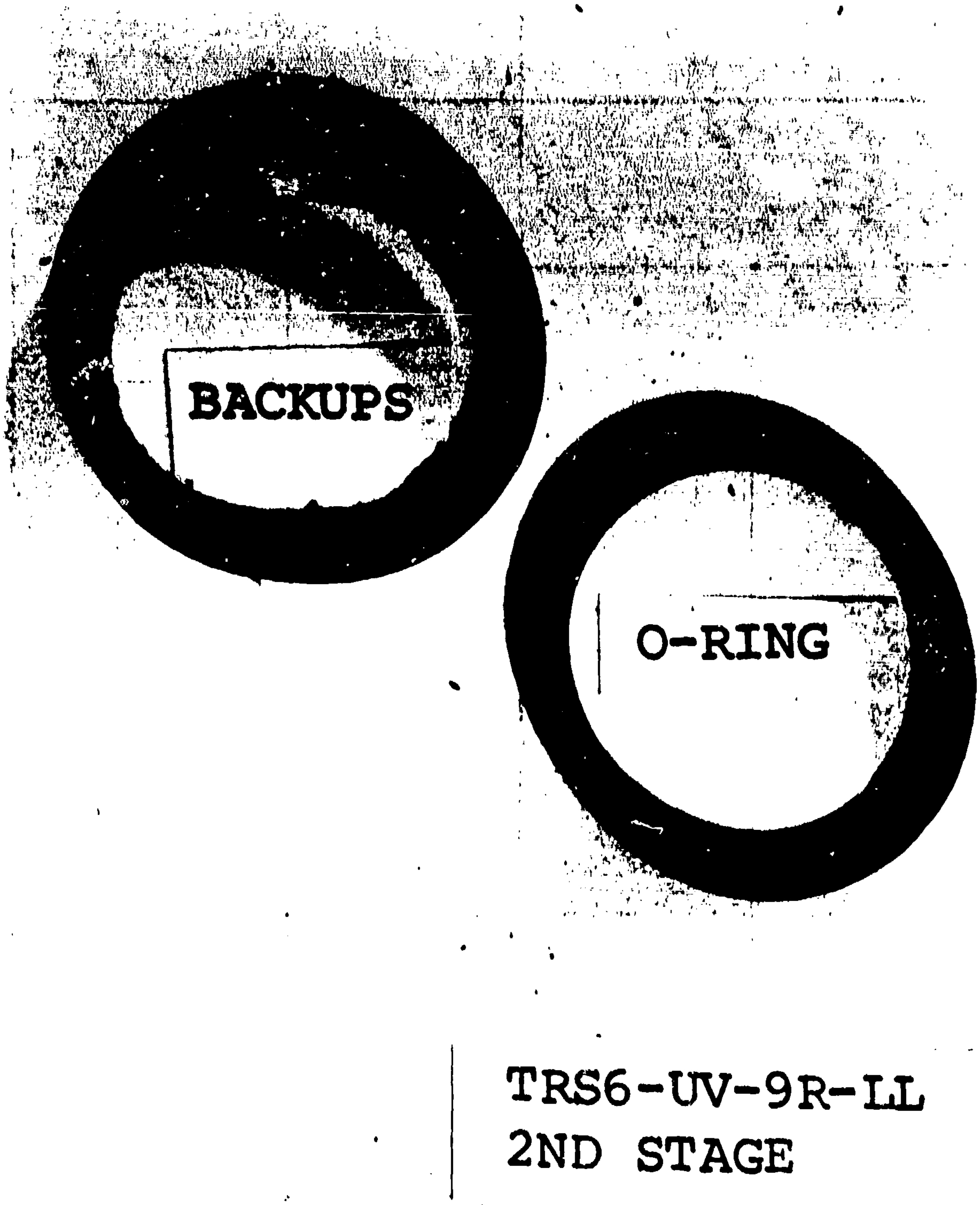


Figure 163. Candidate TRS6-UV (2nd Stage) After Long Life Test. Redundant backups were a loose fit on rod. Two stage installation did not have measurable leakage.

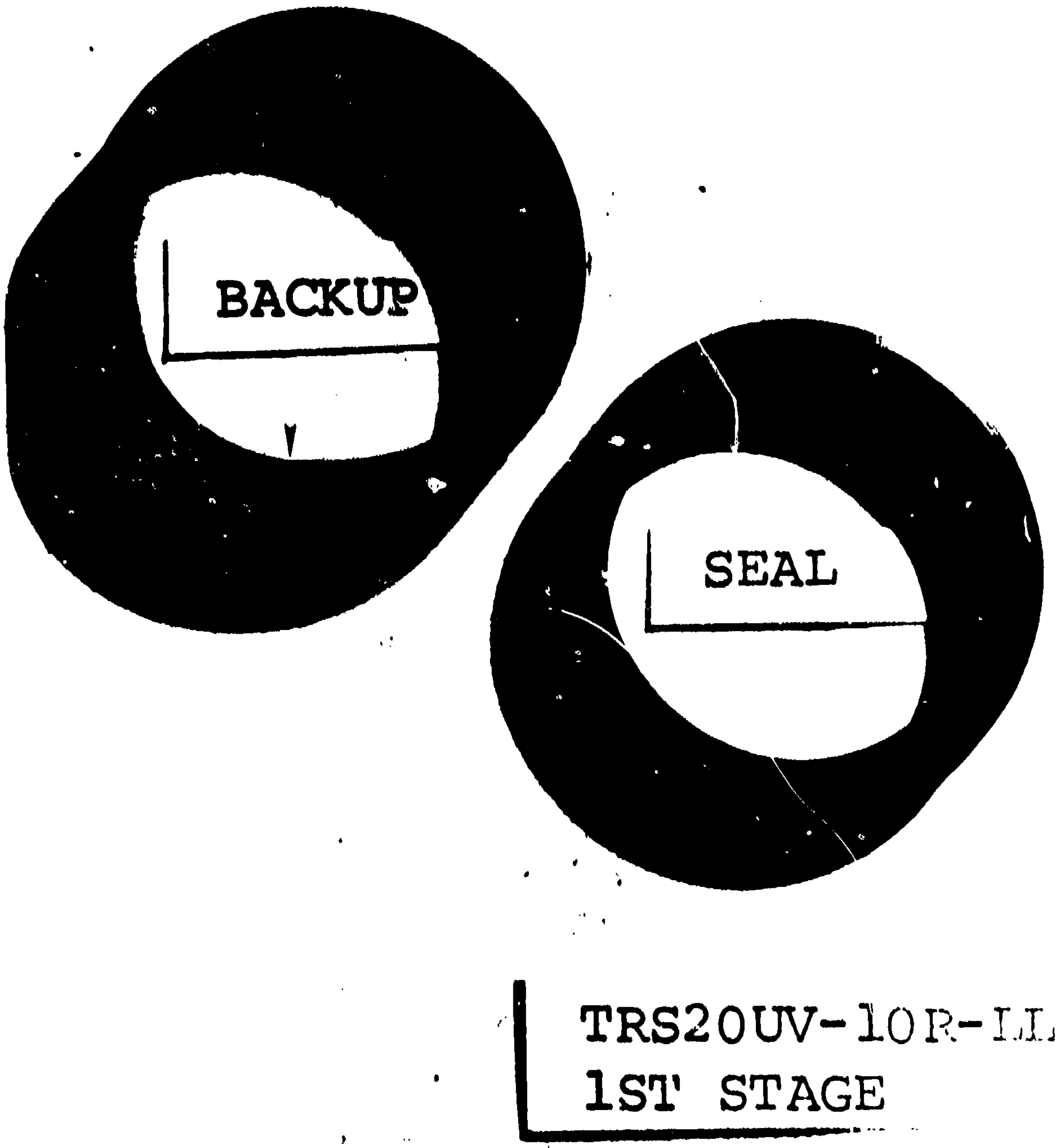


Figure 164. Candidate TRS20-UV (1st Stage) After Long Life Test. Seal and backup are in excellent condition. Backup was nicked (arrow) during removal.

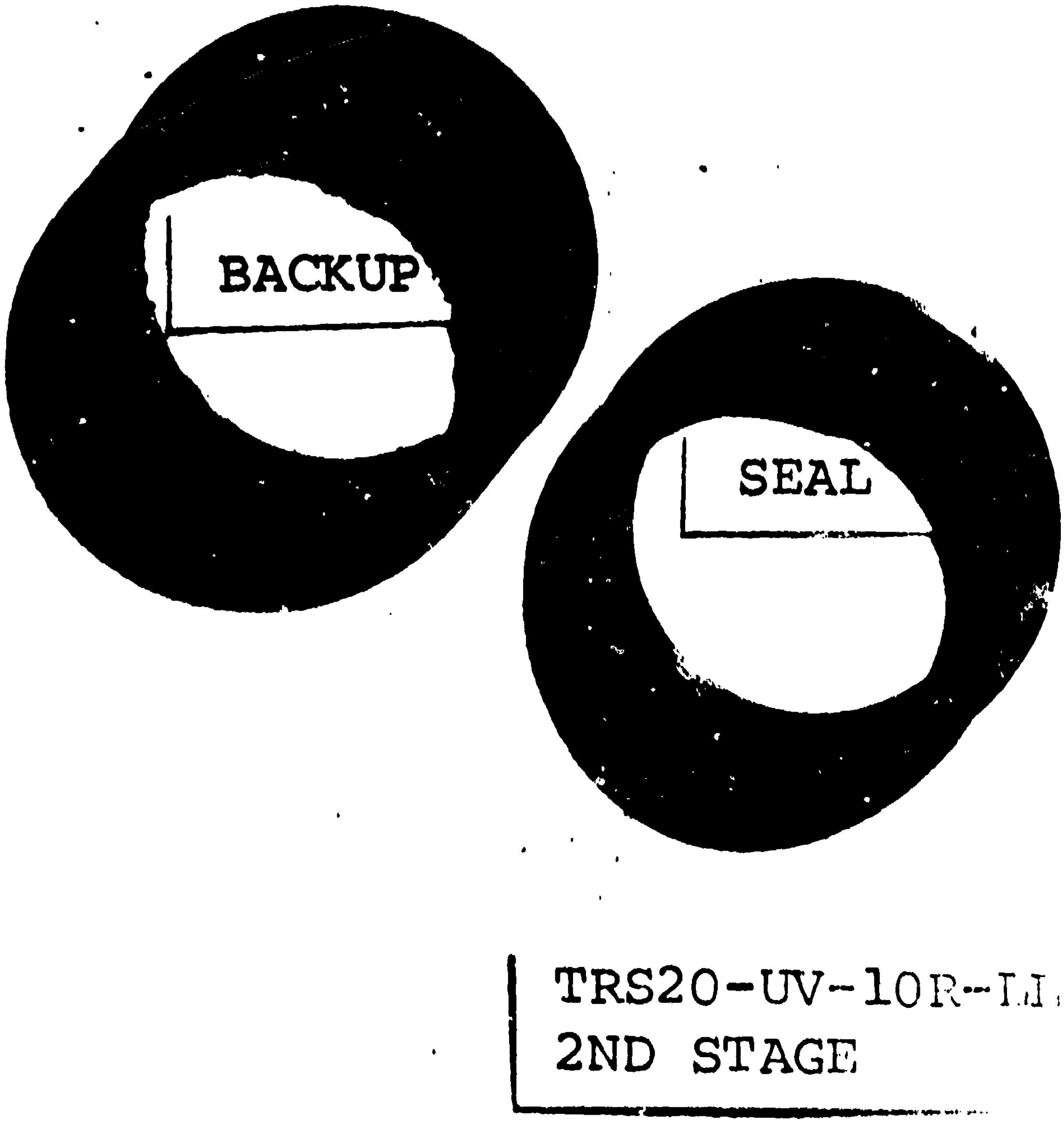


Figure 165. Candidate TRS20-UV (2nd Stage) After Long Life Test. Two stage installation had zero external leakage.

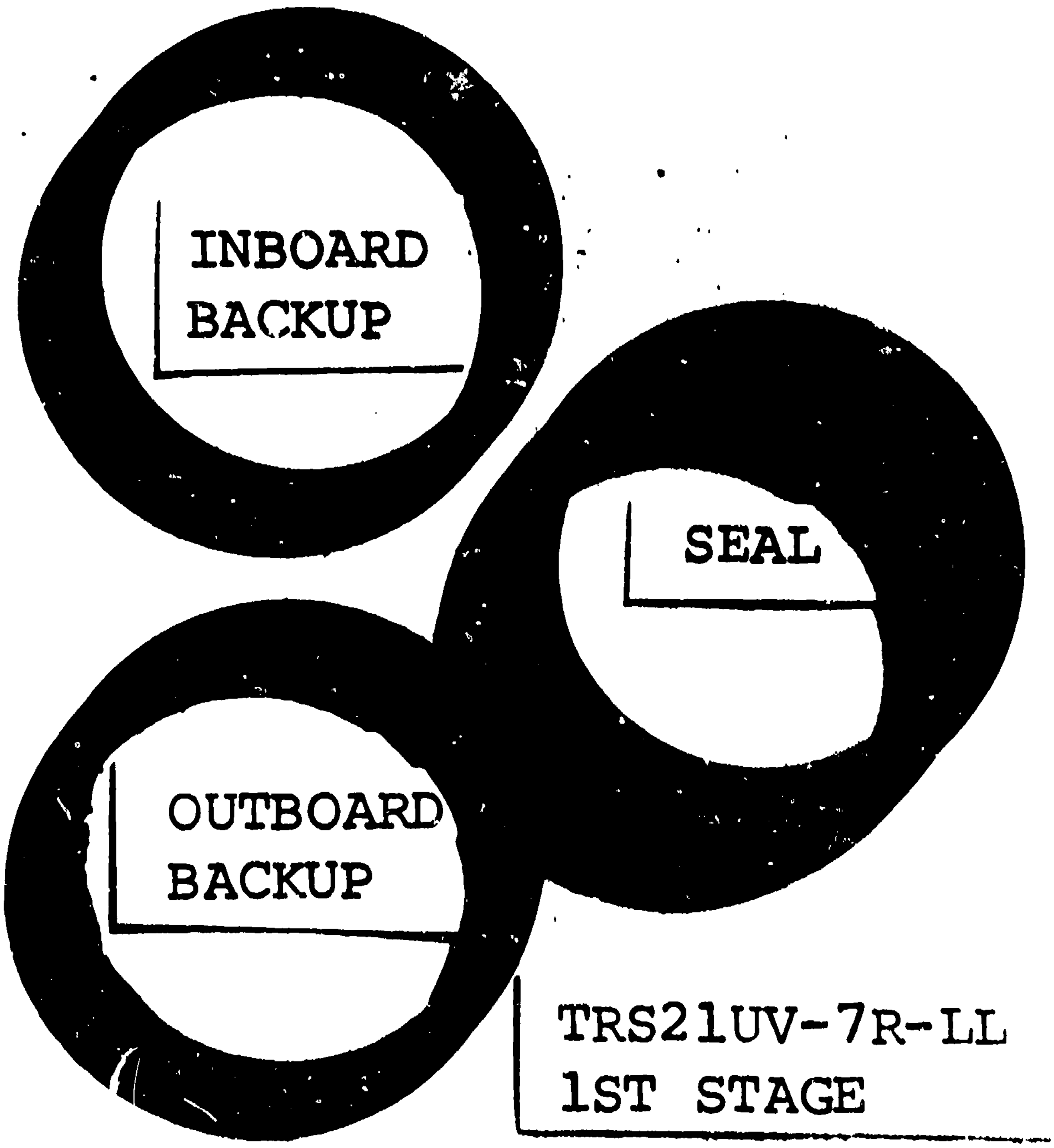


Figure 166. Candidate TRS21-UV (1st Stage) After Long Life Test. Seals is in excellent condition.

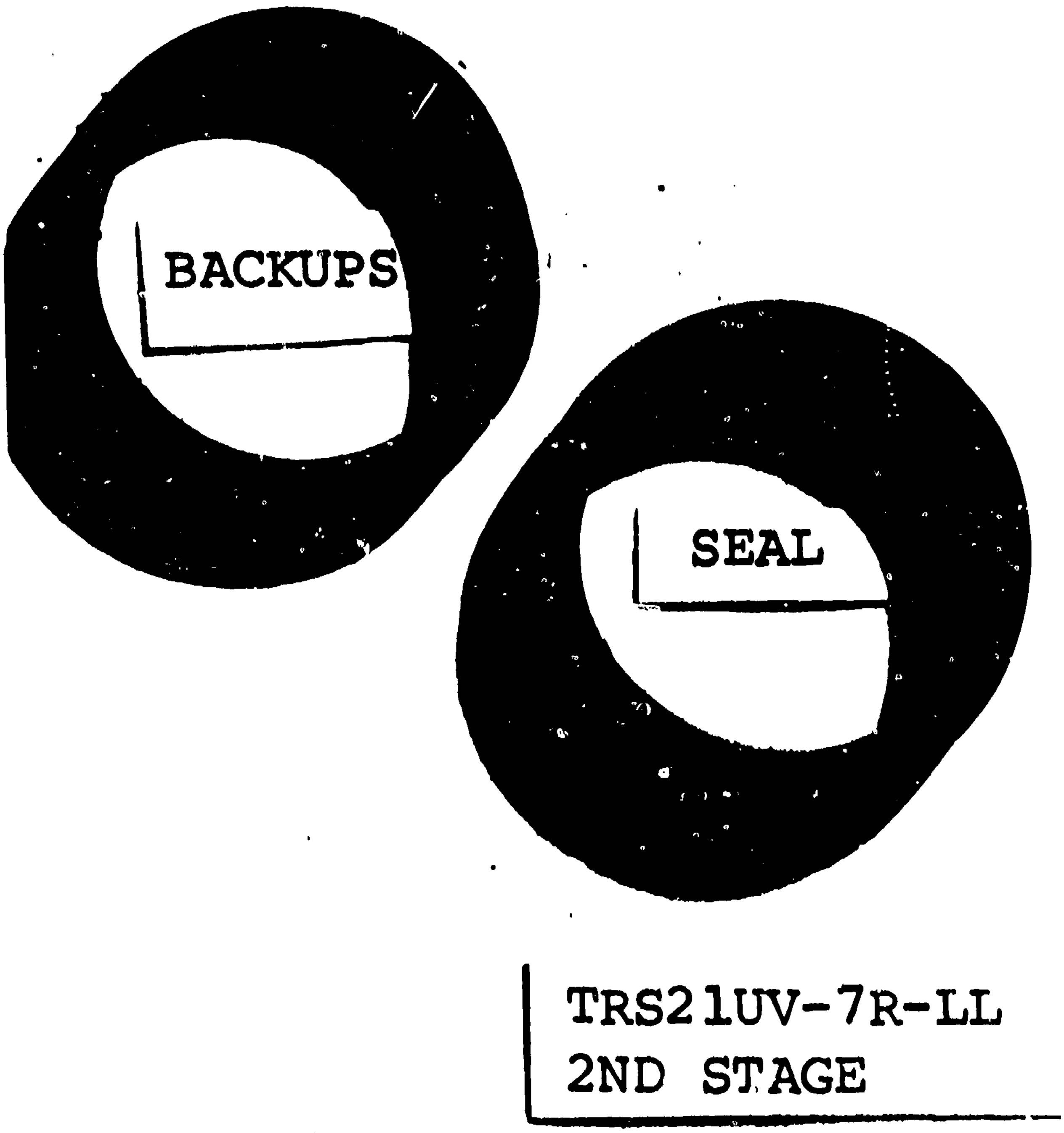


Figure 167. Candidate TRS21-UV (2nd Stage) After Long Life Test. No external leakage occurred.

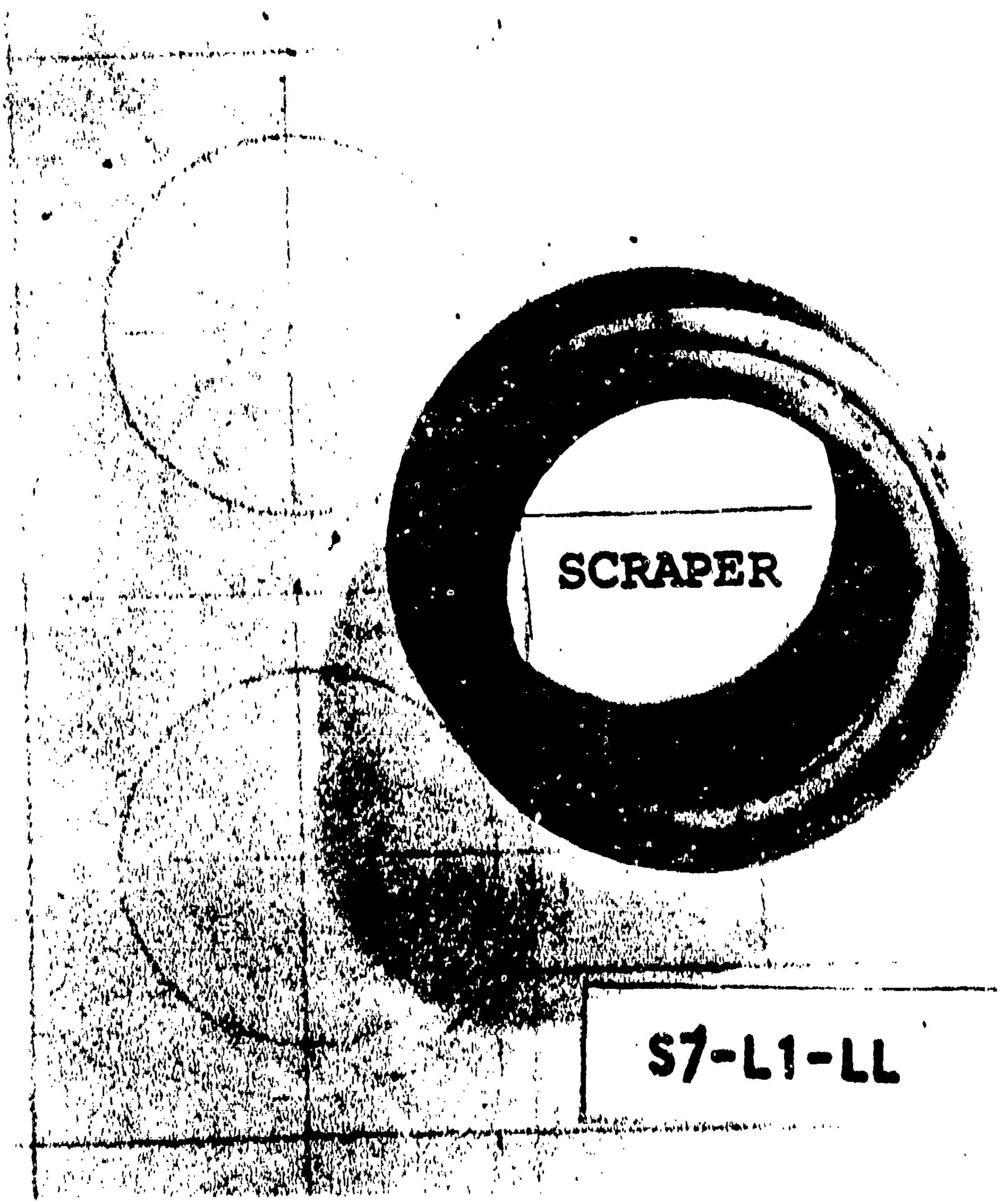


Figure 168. Candidate S7 Scraper After Long Life Test. This sample is representative of the four samples of S7 in the Long Life Test.

5. DISCUSSION OF ANALYTICAL STUDIES CONDUCTED

5.1 Comparison of O-Ring Condition with Several Performance Parameters.

Several comparisons of O-ring condition versus another characteristic were made to see if any correlation can be made to backup performance. The comparisons are only of single stage square or rectangular shape backups which have completed 1.29 x 10^6 to 3.17 x 10^6 cycles of testing. If rod scoring caused removal, the backup was not included in the comparisons.

5.1.1 Leakage versus O-Ring Condition.

The first comparison lists increasing leakage versus O-ring condition. Here, O-ring condition is the actual condition of each O-ring after test. Candidate B25 is not included because leakage is unknown.

Test Leakage - Drops	Candidate	O-Ring Condition
0	B1	G
0	B9	E
0	B16	F
0	B1	G
0	B24	G
1	B33	P
2	B34	G
3	B4	F
5	B2	G
8	B1	F
11	B17	P
12	B5	P
15	B21	P
42	B9	F
248	B5	P
1850	B21	P
Leakage Failure	B1	P
Leakage Failure	B31	P

This comparison, which considers the appearance of the O-ring after test, shows that the O-ring must be severely nibbled before leakage is affected. Candidate B2 leaked five drops with minimum O-ring damage while Candidate B33 had one drop leakage and the O-ring was in poor condition. Of this group, only B21, B1 and B31 failed due to leakage based upon a criteria of 1 drop/25 cycles for 50 and 100 percent cycling plus 2 drop/hour for 1, 2, and 10 percent cycling. Protection of the O-ring is important. Referring back to Table 8, there were no good or excellent condition O-rings which had excessive leakage.

5.1.2 Bore/Rod Diametral Clearance versus O-ring Condition.

The next comparison lists increasing diametral clearance versus O-ring condition. In addition to the constraints listed in paragraph 5.1, this list excludes backups which were not impulse tested. MS28774 (B1) backups used with additional scraper tests but not shown on Table 8 are included in this comparison.

Clearance	Candidate	O-Ring Condition
.0024	B16	F
.0025	B9	E
.0030	B17	P
.0031	B33	P
.0032	B21	P
.0035	B1	P
.0036	B1	G
.0038	B1	F
.0039	B2	G
.0039	B1	P
.0039	B1	P
.0039	B1	P
.0042	B4	F
.0042	B5	P
.0043	B34	G
.0043	B1	P
.0043	B1	P
.0045	B25	P
.0045	B31	P
.0045	B1	P
.0047	B24	G
.0047	B1	P
.0047	B1	P

The comparison shows that O-rings were in poor condition with clearance as low as .0030. O-rings were in good condition with diametral clearance as high as .0047. The range of diametral clearances used in screening tests did not seem to affect backup performance.

5.1.3 Worn Backup Cross Section versus O-ring Condition

The next comparison is backup average cross section dimension after test versus O-ring condition.

Cross Section W - in	Candidate	O-Ring Condition
.0935	B16	F
.09405	B1	F
.1026	B4	F
.1080	B9	F
.1092	B1	F
.1100	B1	G
.11005	B1	P
.1108	B31	P
.1131	B17	P
.1142	B21	P
.1158	B2	G
.1164	B5	P
.1164	B21	P
.1165	B5	P
.1169	B9	E
.118	B25	P
.1185	B24	G
.1189	B33	P
.11905	B26	P
.12165	B32	P

This comparison shows that no rectangular backup maintained the O-ring in excellent condition when W was below .1169 inches. However, a number of backups allowed O-ring damage to the poor condition between .1169 and .12165 inches, indicating other factors must be considered in what makes a good backup.

5.2 Thermal Expansion Study on Backup Rings

In an effort to determine if O-ring nibbling is related to backup ring dimensions at operating temperature, a detail study was made of seven candidates. The study used actual measured dimensions of the groove, bore, and rod. The candidate backups were measured after testing. The measured dimensions were assumed to be at 70° F reference. The equivalent dimensions at 275° F were calculated using published coefficients of thermal expansion.

The diametral clearance of the backup with the rod was determined at 275° F by calculating the clearance assuming no restraint on growth of the backup. The clearance at the backup outer diameter was calculated. If the OD relationship was a clearance at 275° F, zero was subtracted from the ID clearance. If the OD relationship was an interference at 275° F, the amount of OD interference was subtracted from the ID clearance since the backup ring obviously cannot have an OD greater than the groove ID.

Candidate	Material	Backup to Rod Diametral Clearance	O-Ring Cond.	Leakage (Drops)	Relative Cold Flow of Backup
B15	Polyimide (SP-1)	.0020	P	N. A.	None
B21	Glass/MoS_2 Filled TFE	.0076	P	1850	None
B2	Proprietary Filled Turcon	.0088	G	5	Low
B16	Unfilled TFE	.0129	F	0	High
B4	Revonoc 18158	.0129	F	3	High
B3	Proprietary Filled Turcon	.0102	E	2	Low
B8	Unfilled TFE	.0130	E	2	High

The first five backups are uncut, rectangular cross section, and have initial interference fit on the rod. The last two backups form an angle of 55 - 60° F with the rod on the face against the O-ring.

Comparing the first five backups which are similar except for material, the backup diametral clearance does not appear to be related to O-ring condition. A better correlation can be made with the relative cold flow of the material. The materials with no cold flow gave poor O-ring condition. The materials with high cold flow gave only fair O-ring condition. The Shamban compound 18 (proprietary filled Turcon) material with low cold flow gave a good O-ring condition. Figure 169 attempts to graph this relationship using hardness as the X-axis parameter and O-ring condition as the Y-axis parameter. This graph suggests that the ideal backup ring material lies between unfilled TFE with Rockwell hardness of R58 and polyimide (SP-1) with Rockwell hardness of E51.

Since Nylon with a hardness of R118 is too hard as a backup material and unfilled TFE with hardness of R58 is on the soft side, it is estimated an ideal material would have a hardness equal to the average of the two materials. Therefore, (58 + 118)/2 = 88. Perhaps a material with Rockwell hardness of R80 to 90 would make a good backup ring material.

Other material properties should also be considered. An absolute limit on deformation would be that for unfilled TFE. An extrapolation from literature shows that unfilled TFE has a deformation of 48 percent at 3000 psi compressive stress for 1000 hours at 212°F. The deformation of an ideal material would be less than this value for unfilled TFE.

Backup ring shape appears to improve performance. Candidate B3 is the same material as B2 but forms an angle with the rod on the face towards the O-ring. The diametral clearance of B3 was similar to B2, however in two separate tests, O-ring condition was excellent with B3. Candidate B8 is the same material as B16 but forms an angle with the rod on the face toward the O-ring. The diametral clearance of B8 was similar to B16, however in two separate tests, O-ring condition was excellent with B8 despite extreme variation in wear of B8 in the two tests.

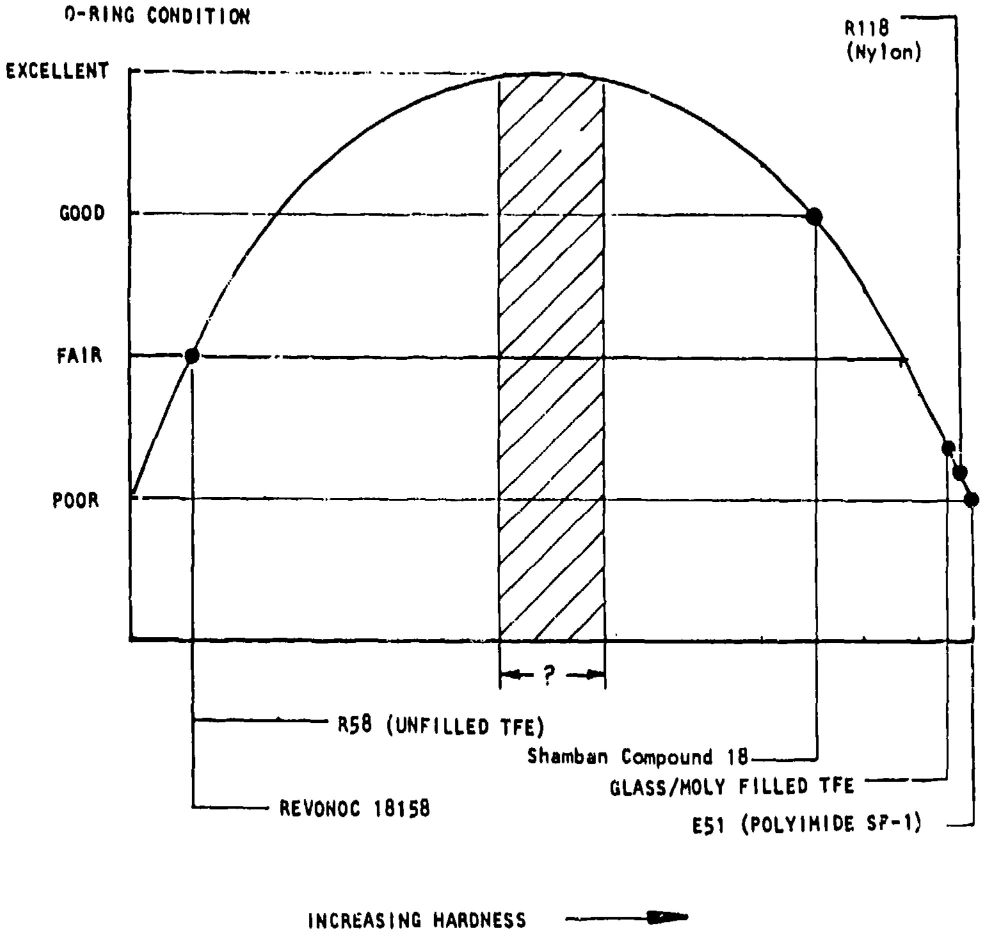


Figure 169. O-Ring Condition Versus Backup Rockwell Hardness

During the Long Life Test and the additional screening test Candidates B23, B30, and B35 were tested. These backups were of three different materials but had the same dimensions and configuration as B3. Three samples of B35 completed the entire 13.31 x 10^6 cycles with an average leakage of only 0.6 drop/day. Four of the five O-rings installed with B23, B30, and B35 were removed in excellent condition.

The large clearances calculated for the seven backups used in the thermal expansion study are probably a factor in O-ring damage. The trapezoid and triangle shaped backups evidently compensate by imposing a radial load into the backup as one of the components of force due to pressure acting on the O-ring. Materials which have relatively high deformation at the test conditions such an unfilled TFE compensate by deforming under load sufficiently to adapt to the rod diameter with changing temperature and pressure. Unfortunately, a material which readily deforms is also subject to extrusion. The amount of initial interference fit can also compensate by making the initial interference fit equal to or greater than the thermal expansion from 70 to 275°F. Ideally, the strain induced by the interference fit should not exceed the strain for the material corresponding to tensile yield strength. Also, the material may experience tensile stress sufficient to yield the plastic when cooled to -65°F.

To summarize; If it is accepted that the O-ring will be protected if the backup maintains intimate contact with the rod, there are three ways to help maintain that contact.

(1) Using a backup material which has sufficient cold flow.

(2) Use an initial interference fit with the rod equal to or greater than the thermal growth anticipated.

(3) Use a triangle or trapezoid shaped backup to utilize a component of pressure loading to overcome growth due to thermal expansion.

5.3 Thermal Expansion Study on Scrapers

The inner diameter of the scraper candidates was measured at room temperature before testing. The diametral fit was calculated at 170° F using the following formula:

$$d_2 \quad d_1 [1 + \alpha \quad (T_2 - T_1)]$$

where: d_2 = diameter at T_2
d_1 = diameter at T_1
α = coefficient of thermal expansion
T_2 = temperature at test condition
T_1 = initial temperature

Table 14 shows the results of the analysis. Three candidates apparently did not have an interference fit with the rod at 170° F which was the minimum ambient temperature for the scraper screening tests. S9 of Hytrel material had .0075 interference initially but had .00181 clearance at 170° F. S9 ranked eleventh in contaminant exclusion. S1 had .0025 interference initially and had .00372 clearance at 170°F. S1 tied for seventh in contaminant exclusion. The wear pattern on the ID indicated that the O-ring energizer helped to maintain a portion of the scraper against the rod. Candidate S7 which ranked third in contaminant exclusion had an .00731 interference fit at 170° F. Candidate S2 had .0040 clearance at 170°F and placed fourth. The O-ring loading evidently compensated for the thermal expansion.

The correlation of contamination exclusion to scraper clearance with the rod suggests that maintenance of contact between the scraper and rod is essential. This is particularly true if the scraper has no positive loading device such as an O-ring to help maintain contact.

TABLE 14. TEMPERATURE EXPANSION ANALYSIS ON SCRAPERS

Candidate	Material	Coefficient of Therm Exp (10^6 in/in/deg F)		Diameter - Inches Scraper 70°	Diameter - Inches Scraper 170°	Rod 70°	Rod 170°	Clearance(+) or Interference (-) at 170°F	Performance Rank
S16	Thermoplastic rubber	100.62		.982	.9918	.99745	.99745	-.00557	1
S19	TFE	69		.982	.98876	.9975	.99815	-.00937	2
S7	Acetal Resin	45	(1)	.986	.99044	.9971	.99775	-.00732	3
			(2)	.9862	.99113	.9979	.99855	-.00742	
S2	TFE	69		.994	1.00086	.9962	.99685	+.00401	4
S17	TFE	69		.982	.98878	.9983	.99894	-.01017	5
S6	Bronze	10.5		.994	.99504	.9984	.99905	-00401	6
S1	TFE	69		.994	1.00086	.9965	.9974	+.00372	7/8
S12	Bronze	10.5	(1)	.990	.99104	.9965	.99713	-.00611	
			(2)	.9903	.99134	.9967	.99735	-.00601	7/8
S8	Polyurethane	100		.982	.99182	.9987	.99935	-.00753	9
S14	Polyurethane	100		.982	.99182	.997	.99765	-.00583	10
S9	Thermoplastic Rubber	100.62		.990	.99996	.9975	.99815	+.00181	11
S15	TFE	69		.982	.98777	.9969	.99755	-.00978	12

Rod coefficient of thermal expansion = 6.5 x 10^6 in/in/deg F.

(1) = First candidate tested
(2) = Second candidate tested

6. DISCUSSION OF ROD WEAR

Two types of rod wear were observed during the tests conducted in this program. The first type of wear is that which is due to the material of the candidate seal or scraper being tested. The second type of wear can be described as scoring or galling of the chrome plate on the rod. Wear due to the elastomers used was negligible.

6.1 Normal Rod Wear Observed Due to Plastic Materials.

For all backups, seals, and scrapers, a total of 22 plastic materials were evaluated. Rod wear was classified as low, moderate, or high.

Low wear is defined as no wear to very superficial evidence of wear. Superficial wear was sometimes characterized by the appearance of small bright spots in the chrome where the highest irregularities in the grind marks had been worn off.

Moderate wear was characterized by axial marks in the chrome, some degree of surface finish change to the extent that axial marks and surface wear had obliterated some of the original nominal 12 - 14 rms surface finish.

High wear is defined the same as moderate wear except number and depth of axial marks are higher and amount of surface area which is affected is higher.

The photographs can be misleading as to severity of wear due to lighting effects and due to the discoloration of the rod by MoS_2 and other dark colored fillers.

Materials which had a tendancy to be abrasive were more abrasive when loaded into the rod by some means. Therefore a material which gives moderate rod wear when tested as a backup or seal may give low rod wear when tested as a scraper.

Table 15 classifies materials according to rod wear observed when the material was tested as a backup, seal, or scraper.

Figures 170 thru 191, selected from the scraper and backup screening tests, show the wear pattern observed for each material.

Figures 192 thru 200, from the single stage rod seal screening tests show the damage to the rod from the high side loads imposed by the short stiff tubing used to plumb the actuators together. Just to the left of the severe damage is the area contacted by the candidate seal.

Figures 201 thru 209, show the rod condition for the various materials after 13.31 x 10^6 cycles of the Long Life Tests.

Figures 210 thru 216, show more detail of the type of wear pattern observed with several of the scraper and backup materials included in the additional screening tests.

TABLE 15. ROD WEAR RATING OF PLASTIC MATERIALS

Material	Supplier	Backup	Seal	Scraper
Unfilled TFE	---	L		
Compound 14	W. S. Shamban	M	M	L
Compound 18	W. S. Shamban	M	M	
Compound 19	W. S. Shamban		L/M	
Compound 20	W. S. Shamban	L		
Compound 99	W. S. Shamban	M		
Revonoc 6200	C. E. Conover	L	L	
Revonoc 18156	C. E. Conover			L
Revonoc 18158	C. E. Conover	L	L	L
Polyimide (SP1)	---	H		
Polyimide (SP21)	---	M		
Tetralon 700	Tetrafluor	L		
Tetralon 720	Tetrafluor	L	L	
Bronze	---			M
Acetal Resin	Tetrafluor	L		L
Polyurethane with MoS_2	Parker Packing			L
Thermoplastic rubber (Hytrel)	Greene, Tweed			L
Polyurethane	Disogrin			L
Nylon	Greene, Tweed	H		
TFE with carbon filler	Tetrafluor	M		L
Acetal Resin with TFE filler	Tetrafluor	M		
Low/High Carbon filled Polymer	Tetrafluor	L		

Legend: L - low
M - moderate
H - high

Figure 170. Revonnc 18156 Scraper Wear on Chrome Rod After Scraper Screening Test (S1; 3.3 x 10^6 cycles). Wear is low.

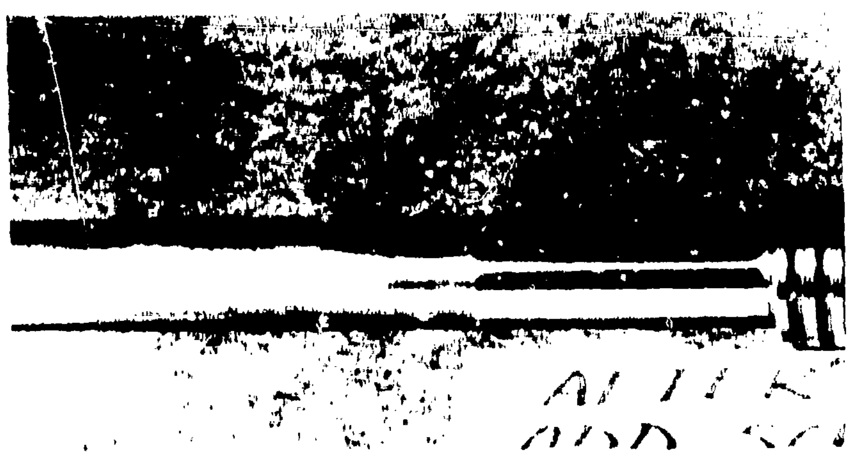


Figure 171. Acetal Resin Scraper Wear on Chrome Rod After Additional Screening Test (S7; 3.3/5 x 10^6 cycles). Wear is low.

Figure 172. Polyurethane with MoS_2 Filler Scraper Wear on Chrome Rod After Scraper Screening Test (S8; 3.3 x 10^6 cycles, Parker Molythane material). Wear is light.

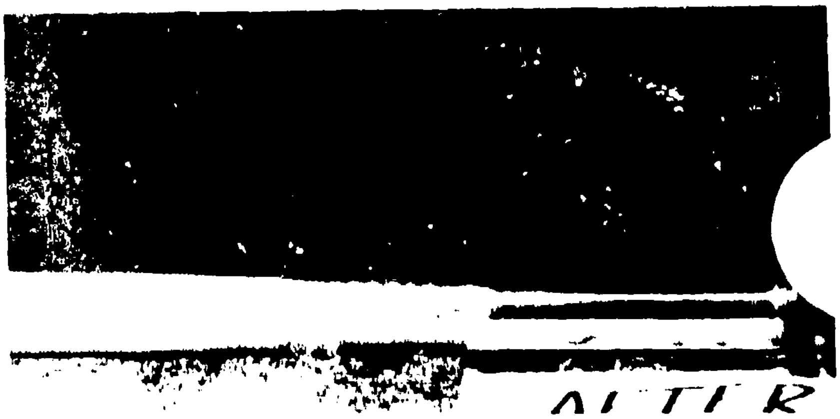


Figure 173. Bronze Scraper Wear on Chrome Rod After Additional Screening Test (S12, MS28776M9, 3.375 x 10^6 cycles). Wear is moderate. Typical for Candidate S6 also.

Figure 174. Polyurethane Scraper Wear on Chrome Rod After Scraper Screening Test (S14; 3.3×10^6 cycles). Wear is light.

Figure 175. Glass/MoS_2 Filled TFE Scraper Wear on Chrome Rod After Scraper Screening Test (Shamban Code 14 material; S15; 3.3×10^6 cycles). Wear is low.

Figure 176. Hytrel Thermoplastic Rubber Scraper Wear on Chrome Rod After Additional Screening Test (S16; 3.375 x 10^6 cycles). Wear is low. Typical for S9 also.

Figure 177. Carbon Filled TFE Scraper Wear on Chrome Rod After Additional Screening Test (S17; 3.375 x 10^6 cycles). Wear is low.

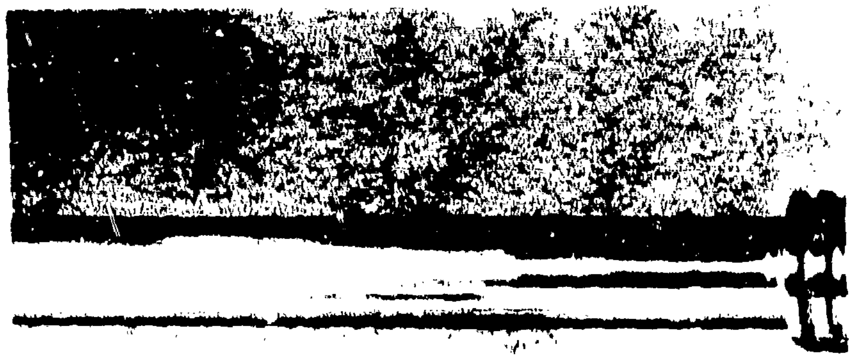


Figure 178. Revonoc 18158 Scraper Wear on Chrome Rod After Additional Screening Test (S19; 3.375 x 10^6 cycles). Wear is low.

Figure 179. Shamban Code 18 Backup Wear on Chrome Rod After Scraper Screening Test (B3; 3.3 x 10^6 cycles). Wear is moderate.

Figure 180. Unfilled TFE Backup Wear on Chrome Rod After Scraper Screening Test (B9; 3.3 x 10^6 cycles). Wear is light. Typical for Candidates B1 and B8.

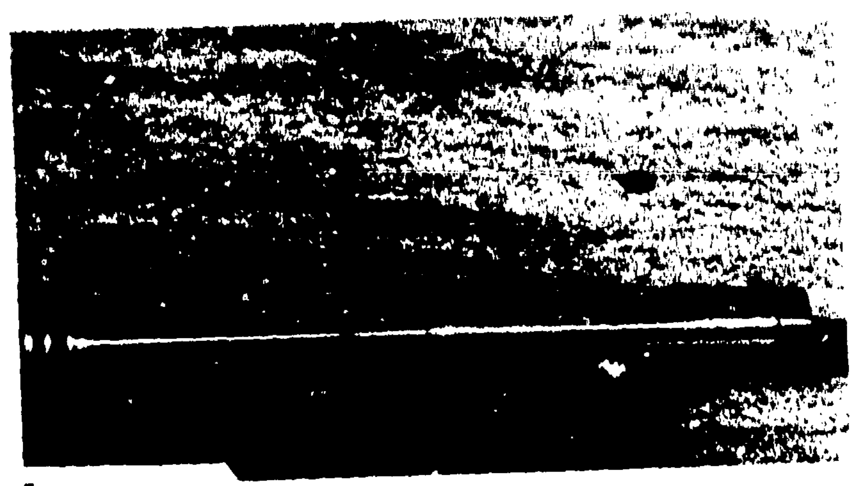


Figure 181. Tetralon 700/Glass/MoS_2 Two Stage Backup Wear on Chrome Rod After Scraper Screening Test (B20; 3.3 x 10^6 cycles). Wear is light.

Figure 182. Glass/MoS_2 Filled TFE Backup Wear on Chrome Rod After Scraper Screening Test (Shamban Code 14 material; B21, 3.3 x 10^6 cycles). Wear is moderate.

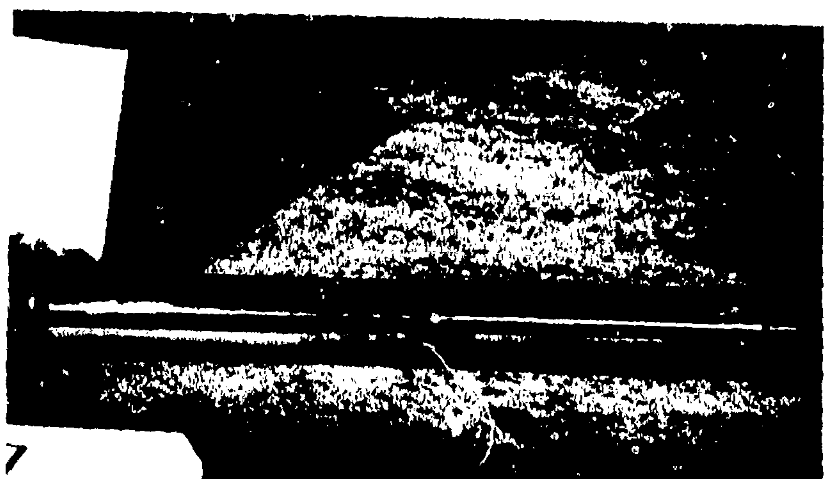


Figure 183. Revonoc 18158 Backup Wear on Chrome Rod After Scraper Screening Test (B22; 3.3 x 10^6 cycles). Wear is low.

Figure 184. Shamban Code 20 Backup Wear on Chrome Rod After Additional Screening Test (B23; 3.375 x 10^6 cycles). Wear is low.

Figure 185. Revonoc 6200 Backup Wear on Chrome Rod After Additional Screening Test (B24; 3.375 x 10^6 cycles). Wear is low.

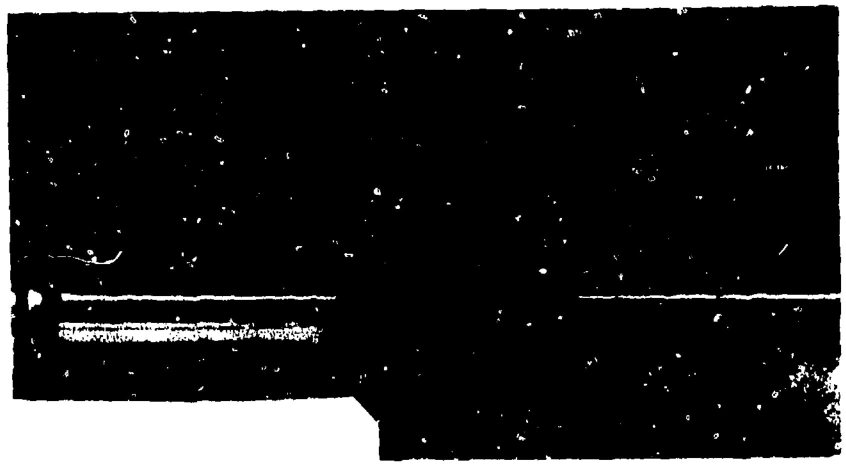


Figure 186. Polyimide (Vespel SP-21) Backup Wear on Chrome Rod After Additional Screening Test (B25; 3.375 x 10^6 cycles). Wear is high.

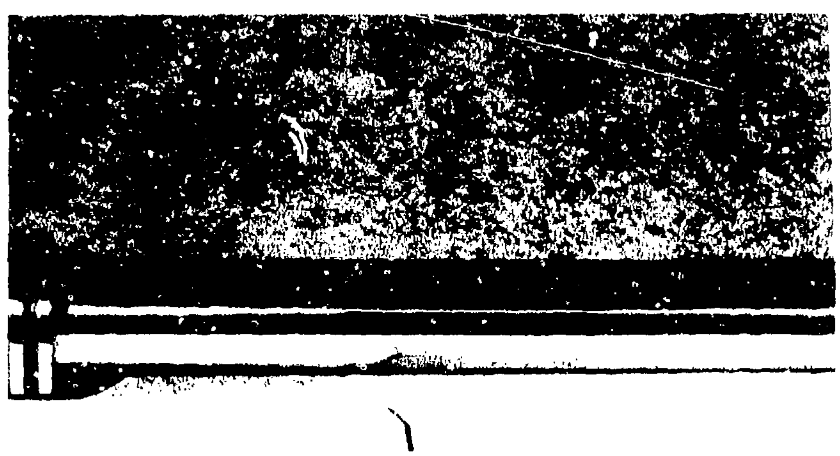


Figure 187. Delrin Acetal Resin Backup Wear on Chrome Rod After Additional Screening Test (B28; 3.375 x 10^6 cycles). Wear is light.

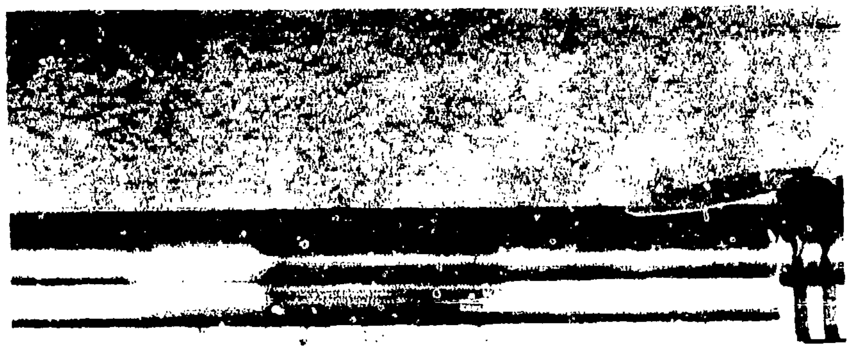


Figure 188. Shamban Code 99 Backup Wear on Chrome Rod After Additional Screening Test (B30; 3.375 x 10^6 cycles). Wear is moderate.

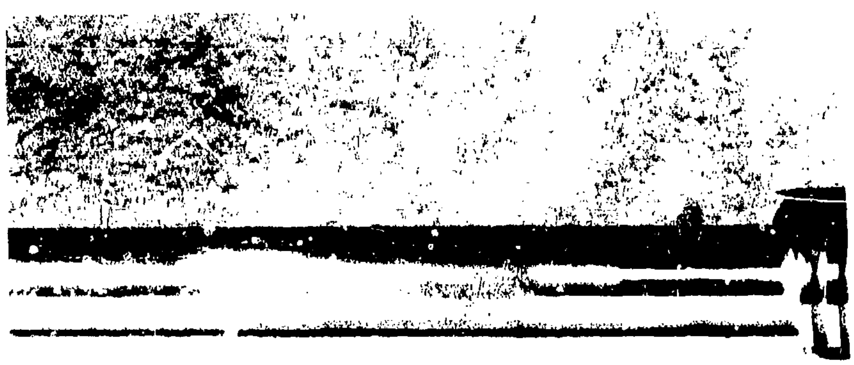


Figure 189. TFE filled Delrin Backup Wear on Chrome Rod After Additional Screening Test (B31, 3.375 x 10^6 cycles). Wear is high.

Figure 190. Tetrafluor Low Fill Carbon Polymer Backup Wear After Additional Screening Test (B32; 1.275 x 10^6 cycles). Wear is low. Typical for B34 also. Arrows denote damage due to scoring, see paragraph 6.2.

Figure 191. Carbon filled TFE Backup Wear on Chrome Rod After Additional Screening Test (B33; 1.85 x 10^6 cycles). Wear is moderate.

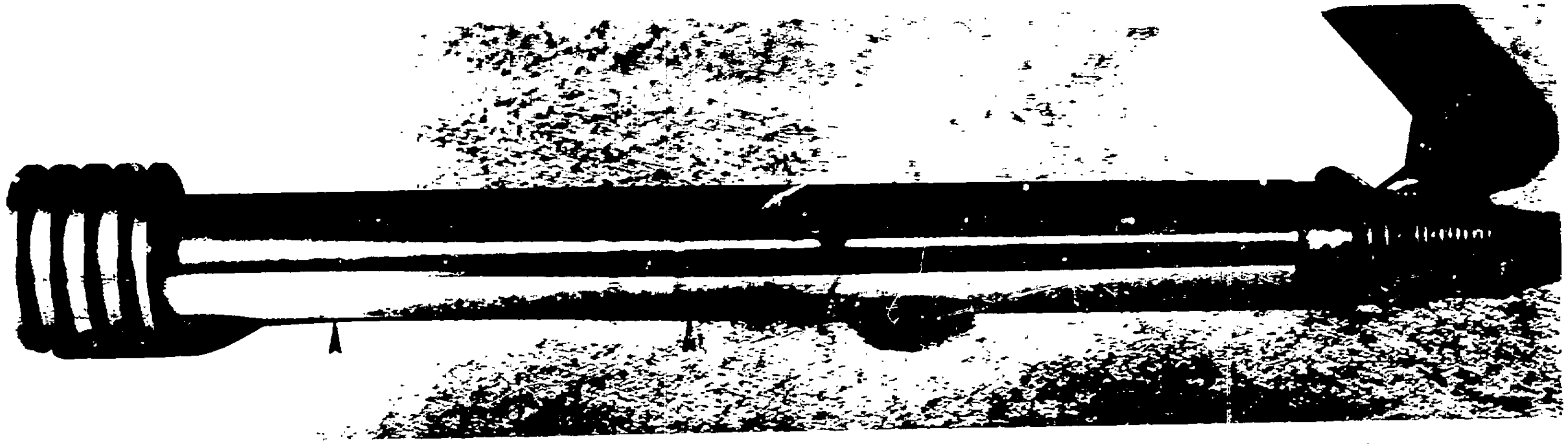


Figure 192. Nitrile/TFE/Nylon ("GT") Seal Rod Wear. Area contacted by RS3 seal is denoted by arrows. Wear is moderate.

Figure 193. Shamban Code 18 Seal Rod Wear. Area contacted by RS7 seal is denoted by arrows. Wear is low. (13.31×10^6 cycles).

Figure 194. Tetralon 720 Seal Rod Wear. Area contacted by RS24 seal is denoted by arrows. Wear is low.

Figure 195. Shamban Code 14 Seal Rod Wear. Area contacted by RS25 seal is denoted by arrows. Wear is low.

Figure 196. Revonoc 6200 Seal Rod Wear. Area contacted by RS26 seal is denoted by arrows. Wear is low.

Figure 197. Unfilled TFE/Nitrile Seal Rod Wear. Area contacted by RS27 seal is denoted by arrows. Wear is low.

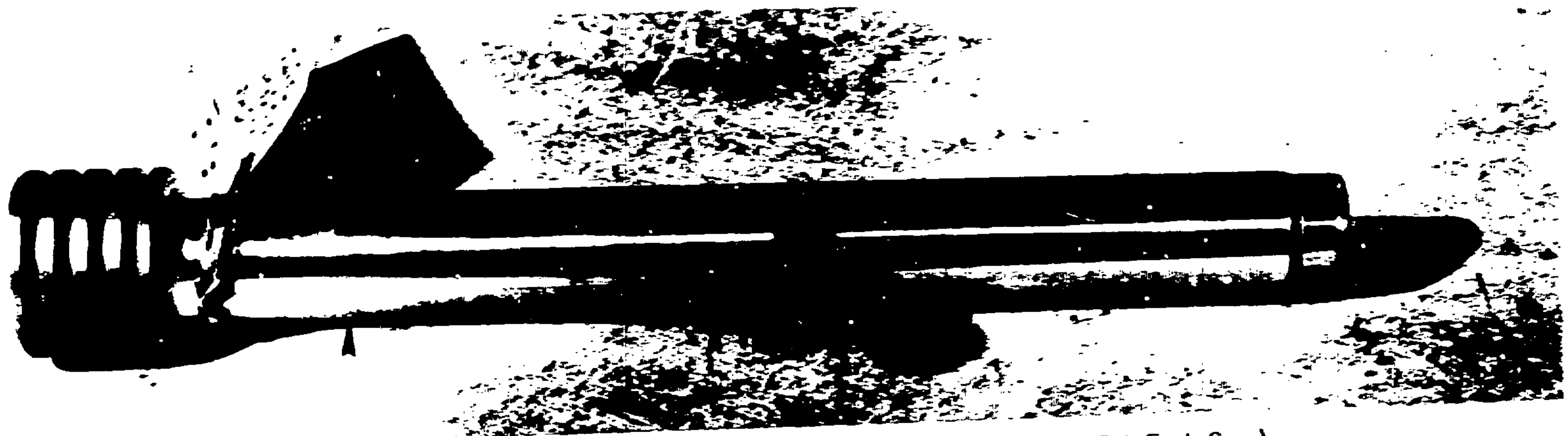


Figure 198. Hytrel Seal/Nylon Backup Rod Wear (17-4 PH End Cap). Area contacted by RS28 seal is denoted by arrows. Rod was in 17-4 PH end caps. Wear is high.

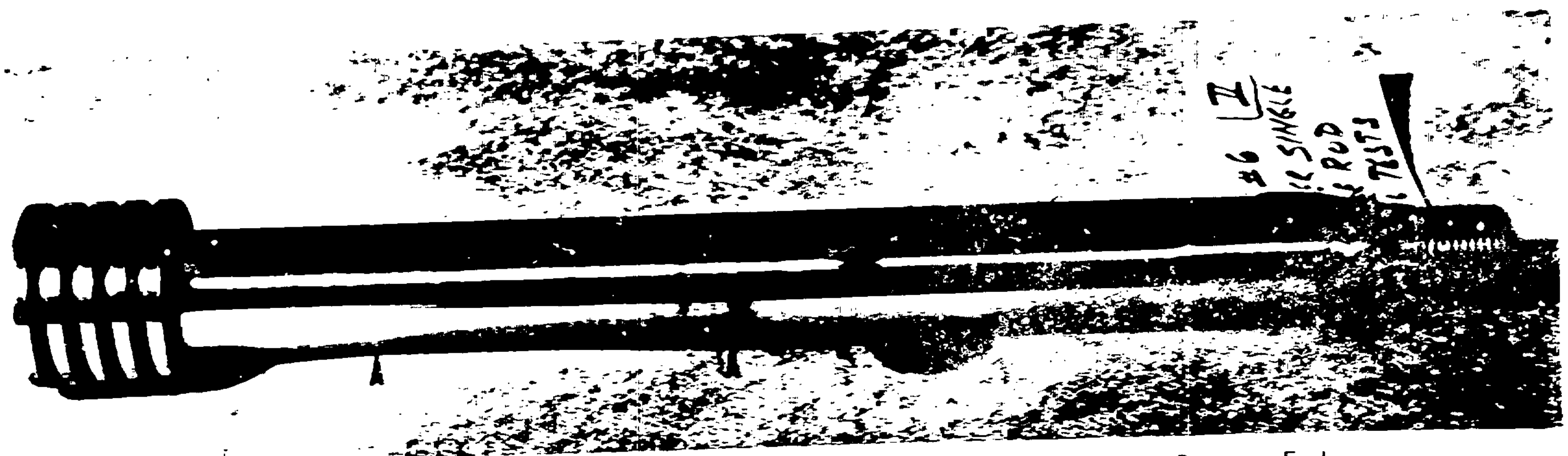


Figure 199. Hytrel Seal/Nylon Backup Rod Wear (Aluminum Bronze End Cap). Area contacted by RS28 seal is denoted by arrows. Rod was in aluminum bronze end cap. Compare with Figure 198. Wear is moderate.

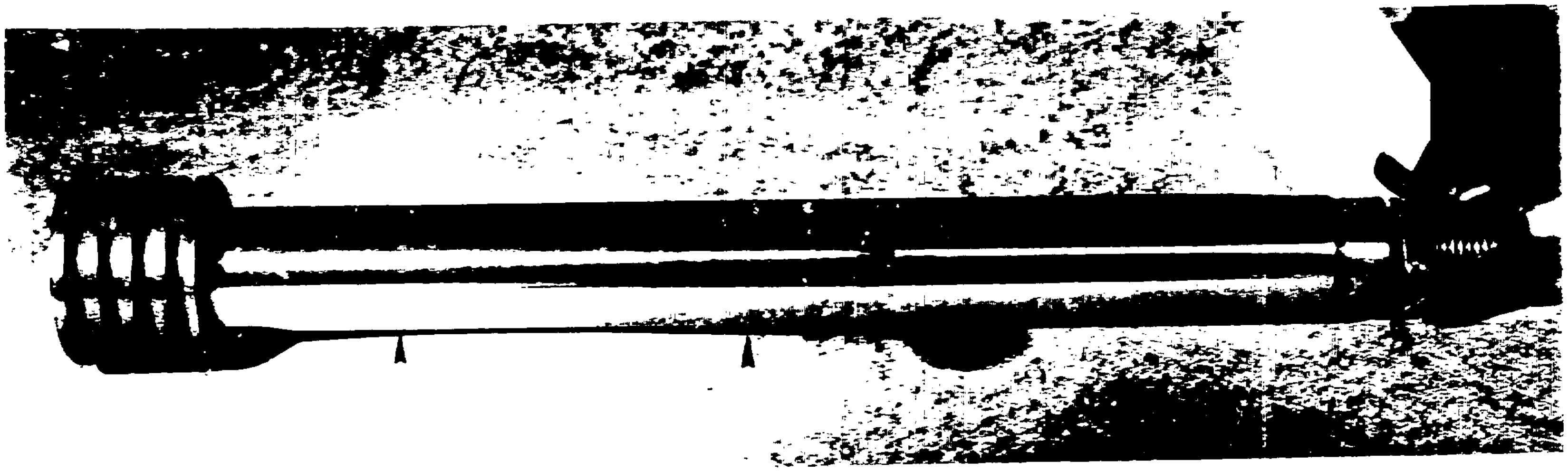


Figure 200. Revonoc 18158 Seal Rod Wear. Area contacted by RS29 seal is denoted by arrows. Wear is very low.

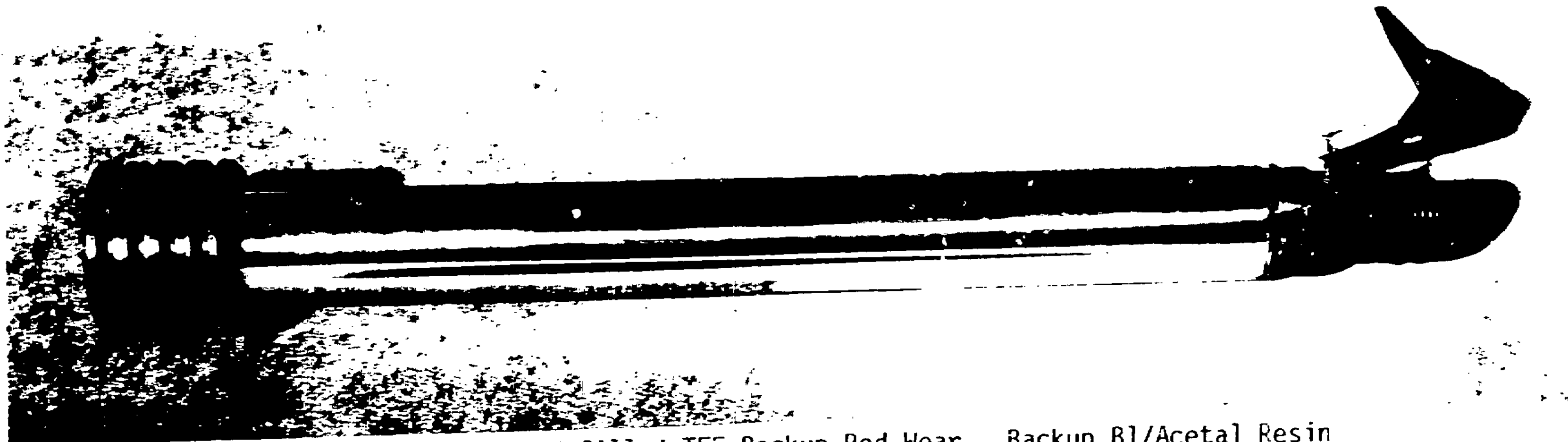


Figure 201. Unfilled TFE Backup Rod Wear. Backup B1/Acetal Resin Scraper rod wear is low after 13.31 x 10^6 cycles.

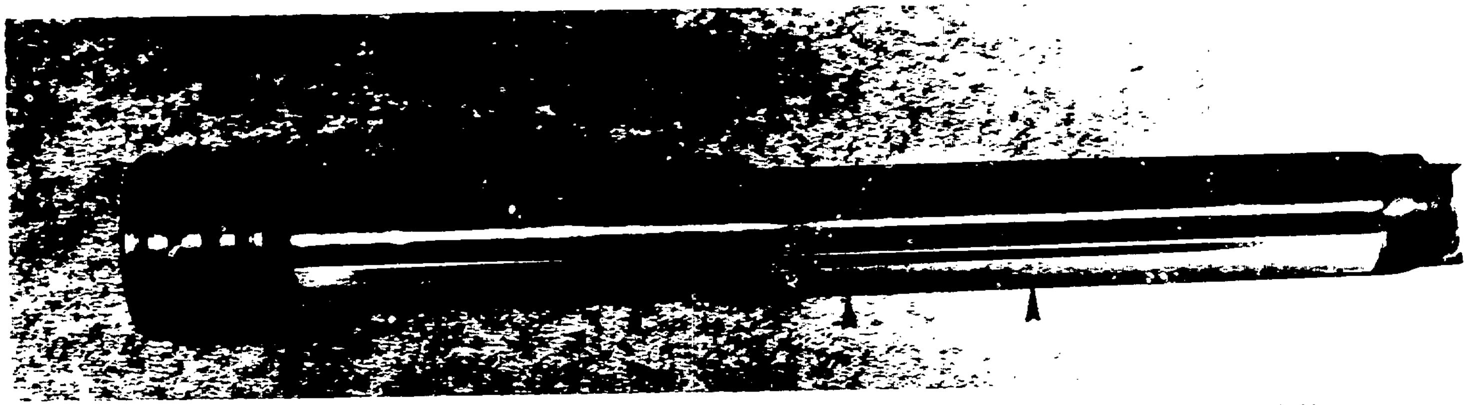


Figure 202. Revonoc 18158 Backup/Acetal Resin Scraper Rod Wear. Going from left to right, arrows denote area contacted during 1 and 2 percent stroke cycling by seal (B22), seal plus scraper, and scraper (S7). (13.31×10^6 cycles).

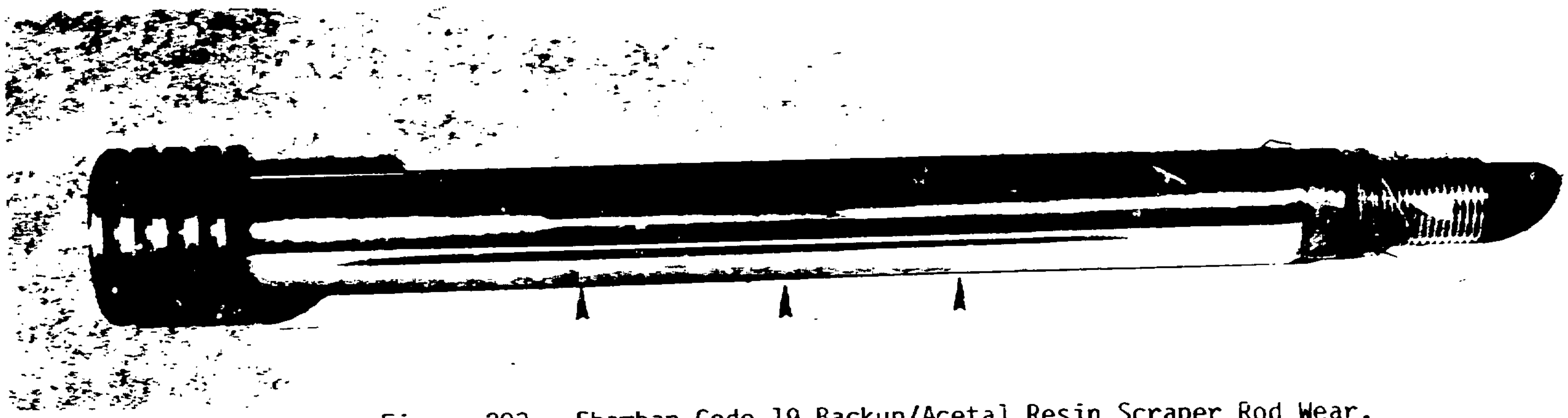


Figure 203. Shamban Code 19 Backup/Acetal Resin Scraper Rod Wear. Going from left to right. Arrows denote area contacted during 1 and 2 percent stroke cycling by seal (B35), seal plus scraper, and scraper (S7). CRES end cap. (13.31×10^6 cycles).

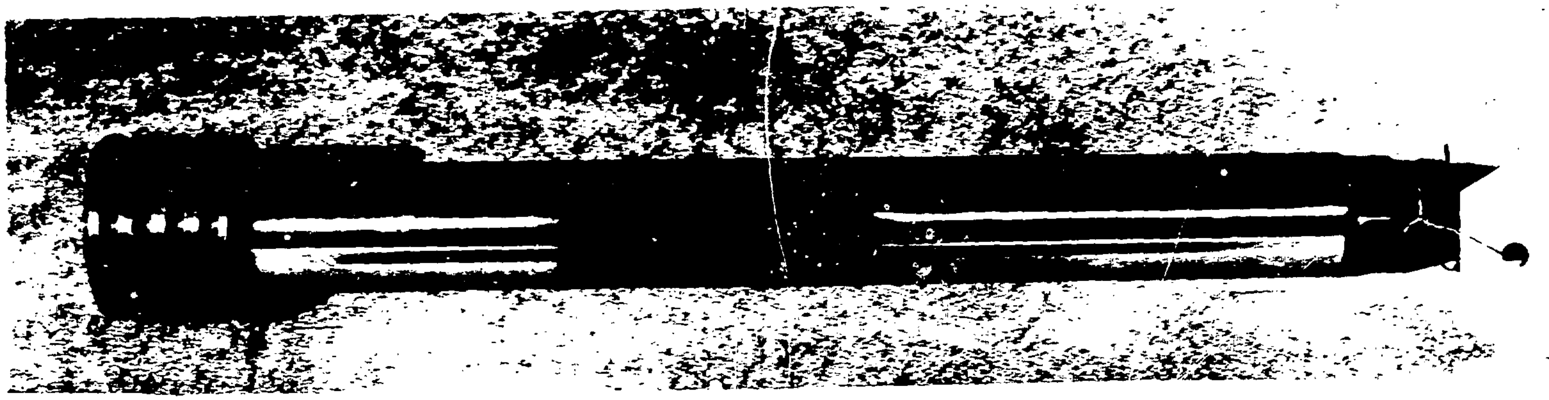


Figure 204. Backup B35 Shamban Code 19 Backup/Aluminum Bronze End Cap Rod Wear. Compare with Figure 203 and 205.

Figure 205. Shamban Code 19 Backup/PNF O-ring/Acetal Resin Scraper Rod Wear. Backup 35 was installed with PNF O-ring. No external leakage occurred. Going from left to right, arrows denote area contacted during 1 and 2 percent cycling by seal (B35), seal plus scraper, and scraper (S7).

Figure 206. Shamban Code 99 Seal Rod Wear. In presence of side loading RS7 seal of Shamban Code 99 material exhibited rod wear. (13.31×10^5 cycles).

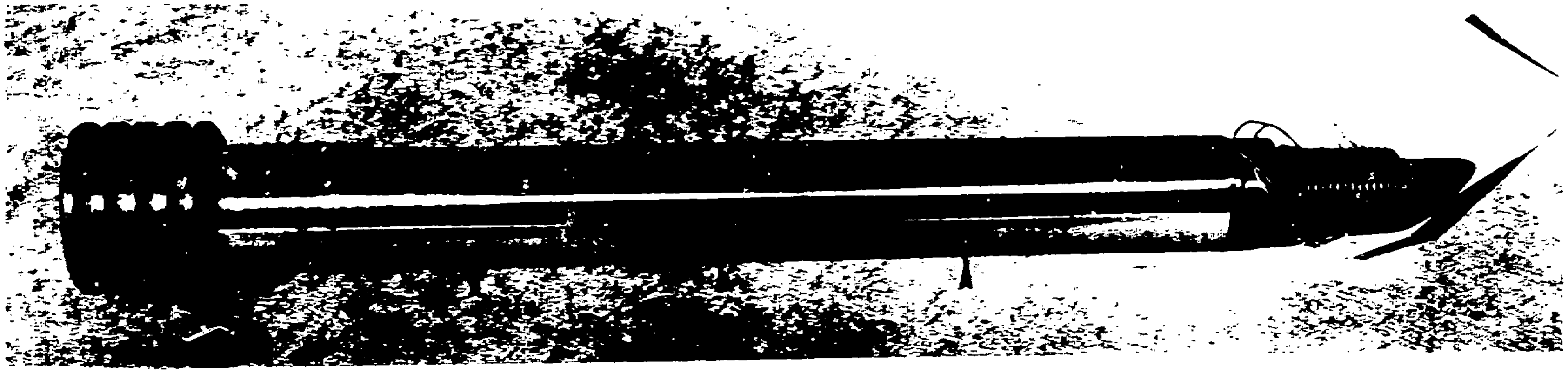


Figure 207. Revonoc 18158 Two Stage Seal Rod Wear. Going from left to right, arrows denote area contacted during 1 and 2 percent stroke cycling by inner seal, both seals, and outer seal (TRS4-UV, 13.31×10^6 cycles).

Figure 208. Shamban Code 99 Two Stage Seal Rod Wear. Going from left to right, arrows denote area contacted during 1 and 2 percent stroke cycling by inner seal, both seals, and outer seal (TRS20-UV, 13.31 x 10^6 cycles).

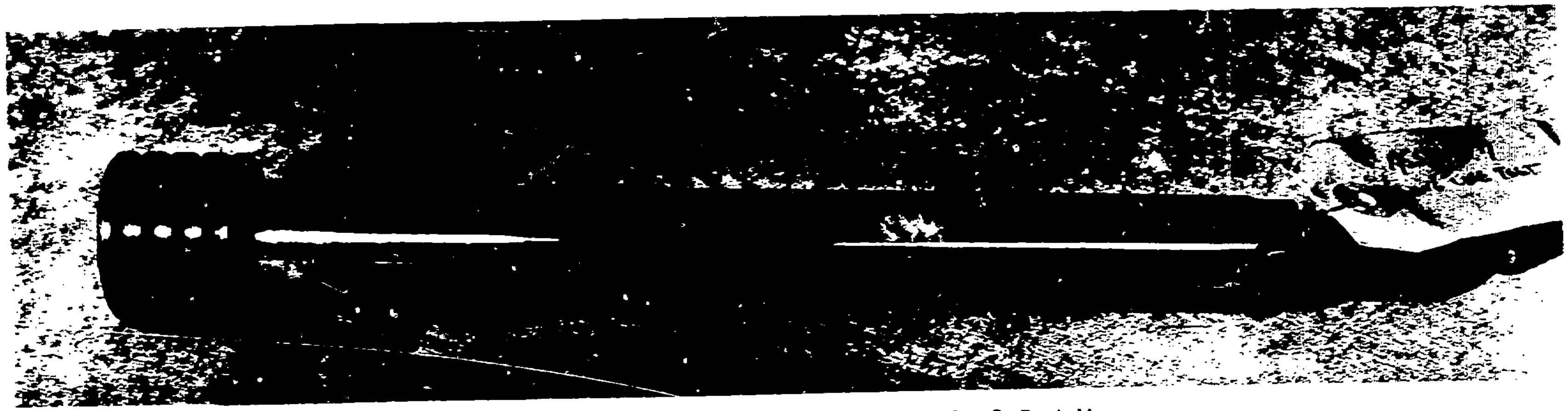


Figure 209. Shamban Code 19 Two Stage Seal Rod Wear. Going from left to right, arrows denote area contacted during 1 and 2 percent stroke cycling by inner seal, both seals, and outer seal (TRS21-UV, 13.31 x 10^6 cycles).

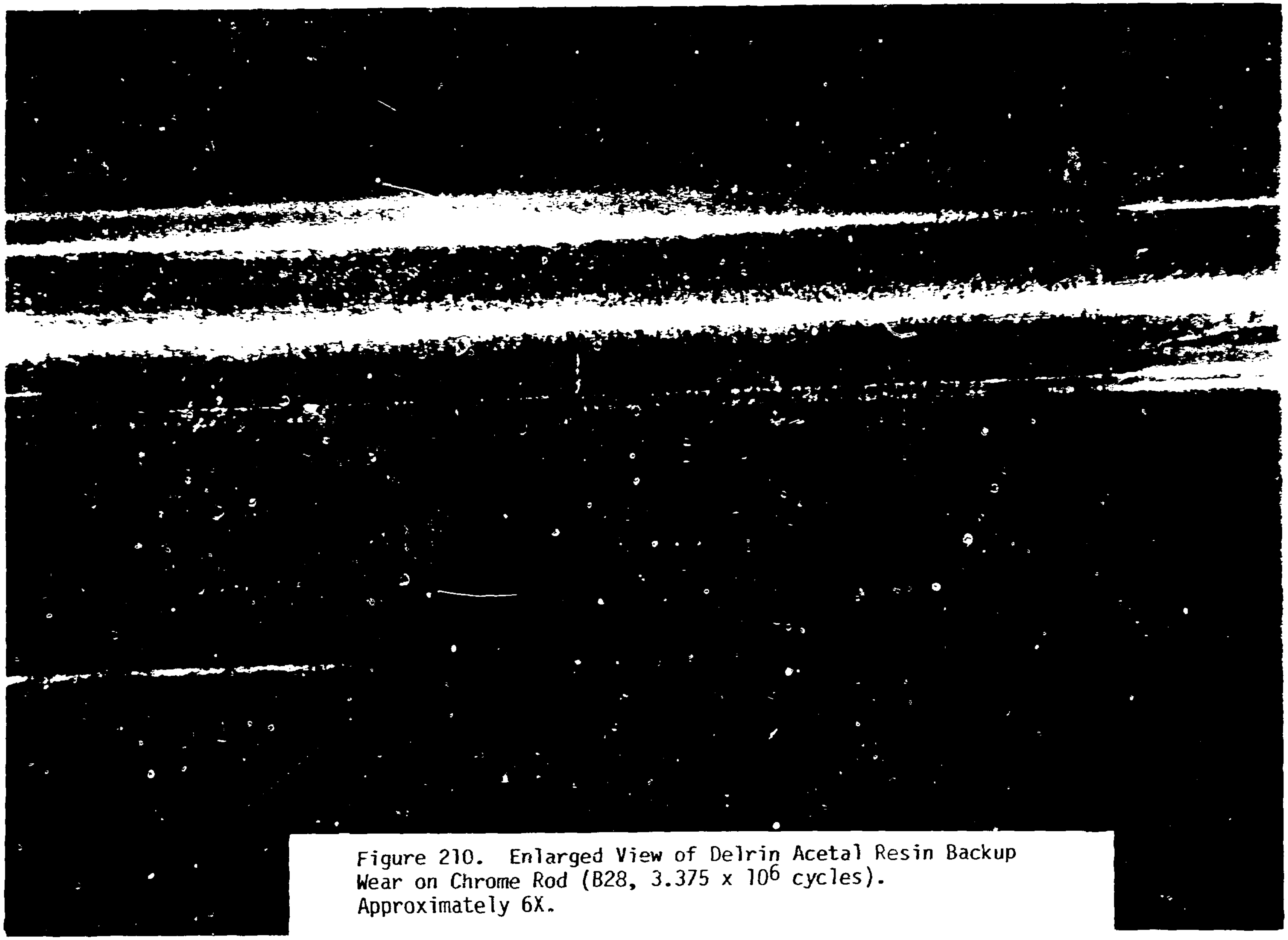


Figure 210. Enlarged View of Delrin Acetal Resin Backup Wear on Chrome Rod (B28, 3.375 x 10^6 cycles). Approximately 6X.

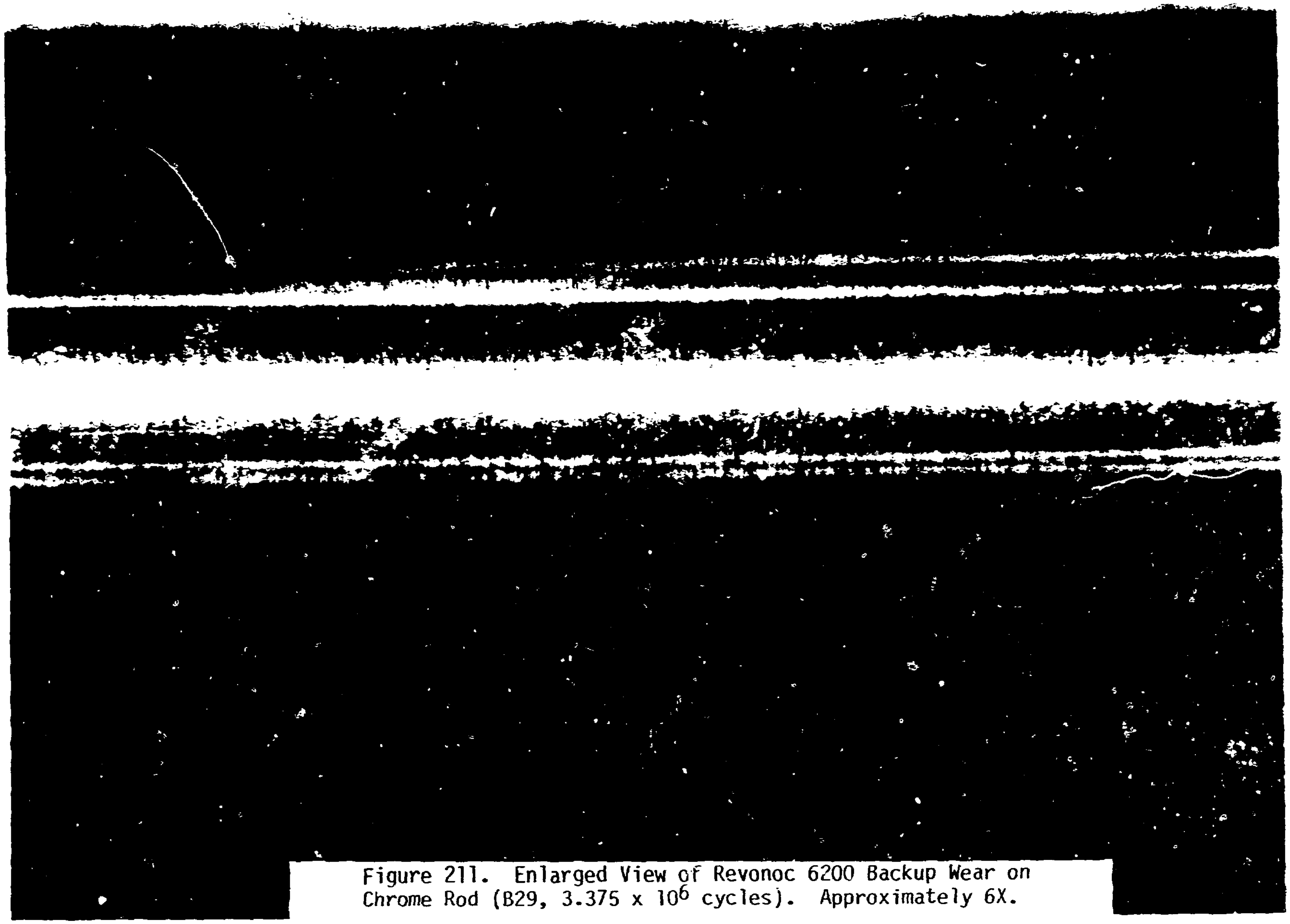


Figure 211. Enlarged View of Revonoc 6200 Backup Wear on Chrome Rod (B29, 3.375×10^6 cycles). Approximately 6X.

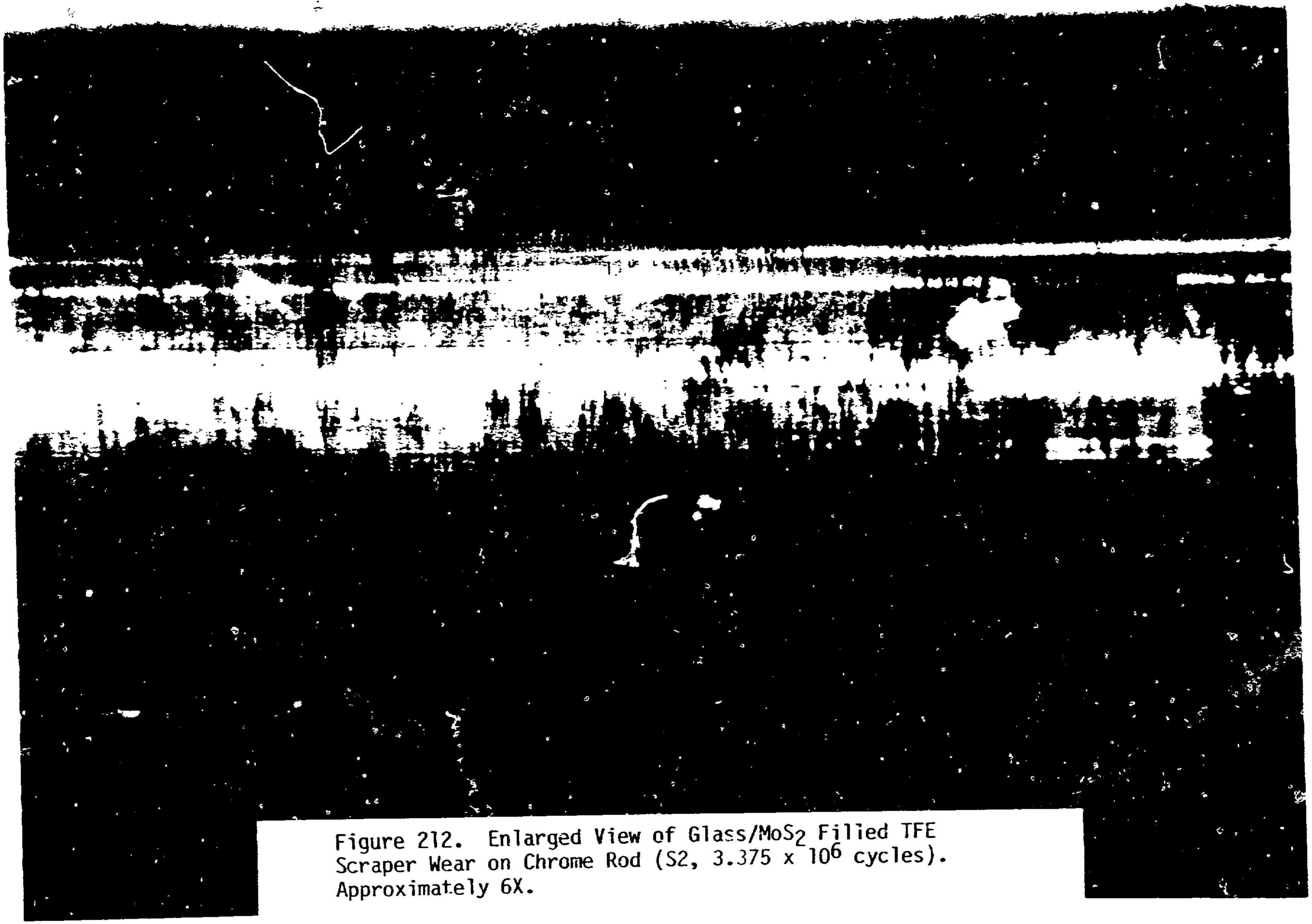


Figure 212. Enlarged View of Glass/MoS_2 Filied TFE Scraper Wear on Chrome Rod (S2, 3.375×10^6 cycles). Approximately 6X.

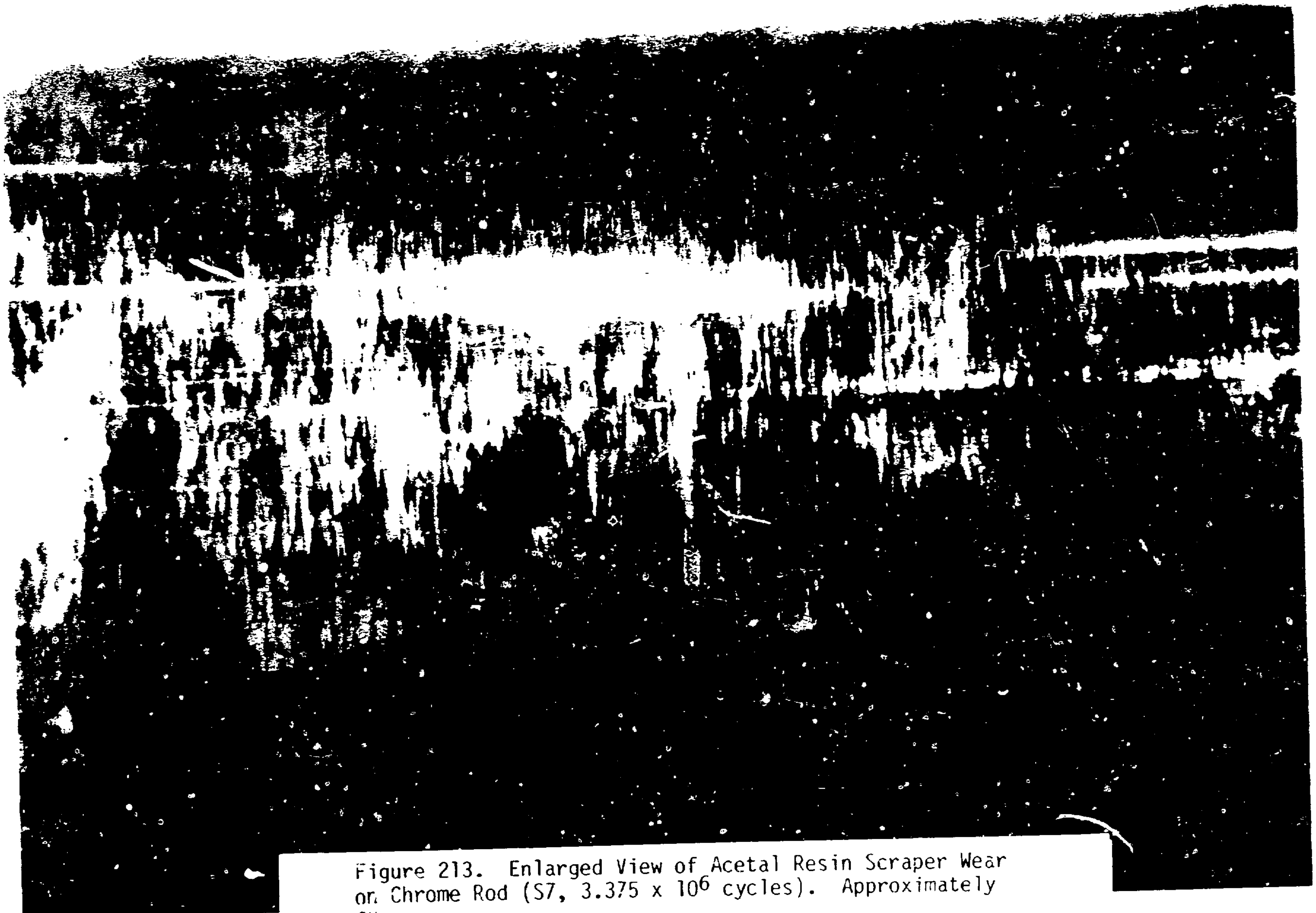


Figure 213. Enlarged View of Acetal Resin Scraper Wear on Chrome Rod (S7, 3.375 x 10^6 cycles). Approximately 6X.

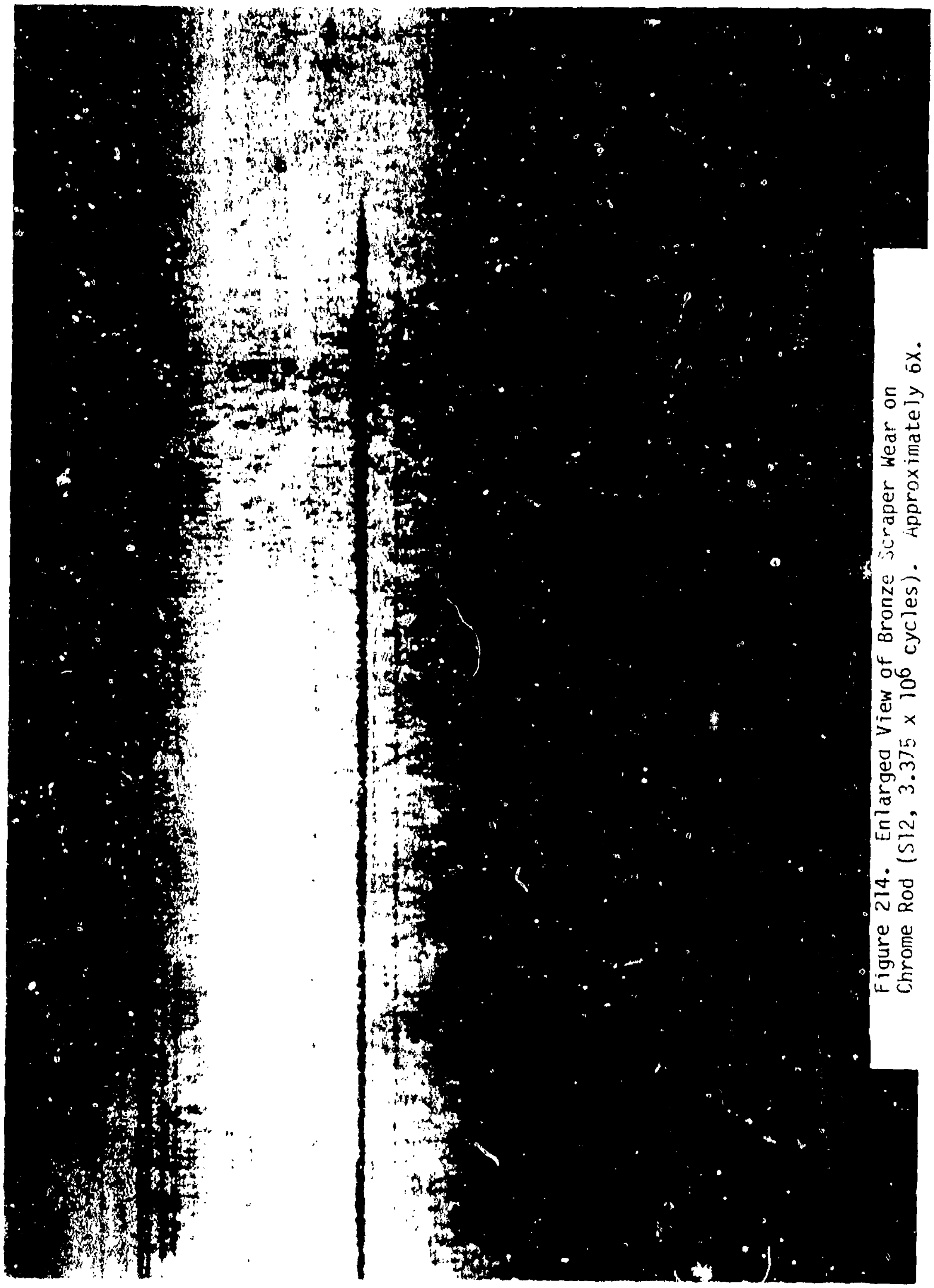


Figure 214. Enlarged View of Bronze Scraper Wear on Chrome Rod (S12, 3.375 x 10^6 cycles). Approximately 6X.

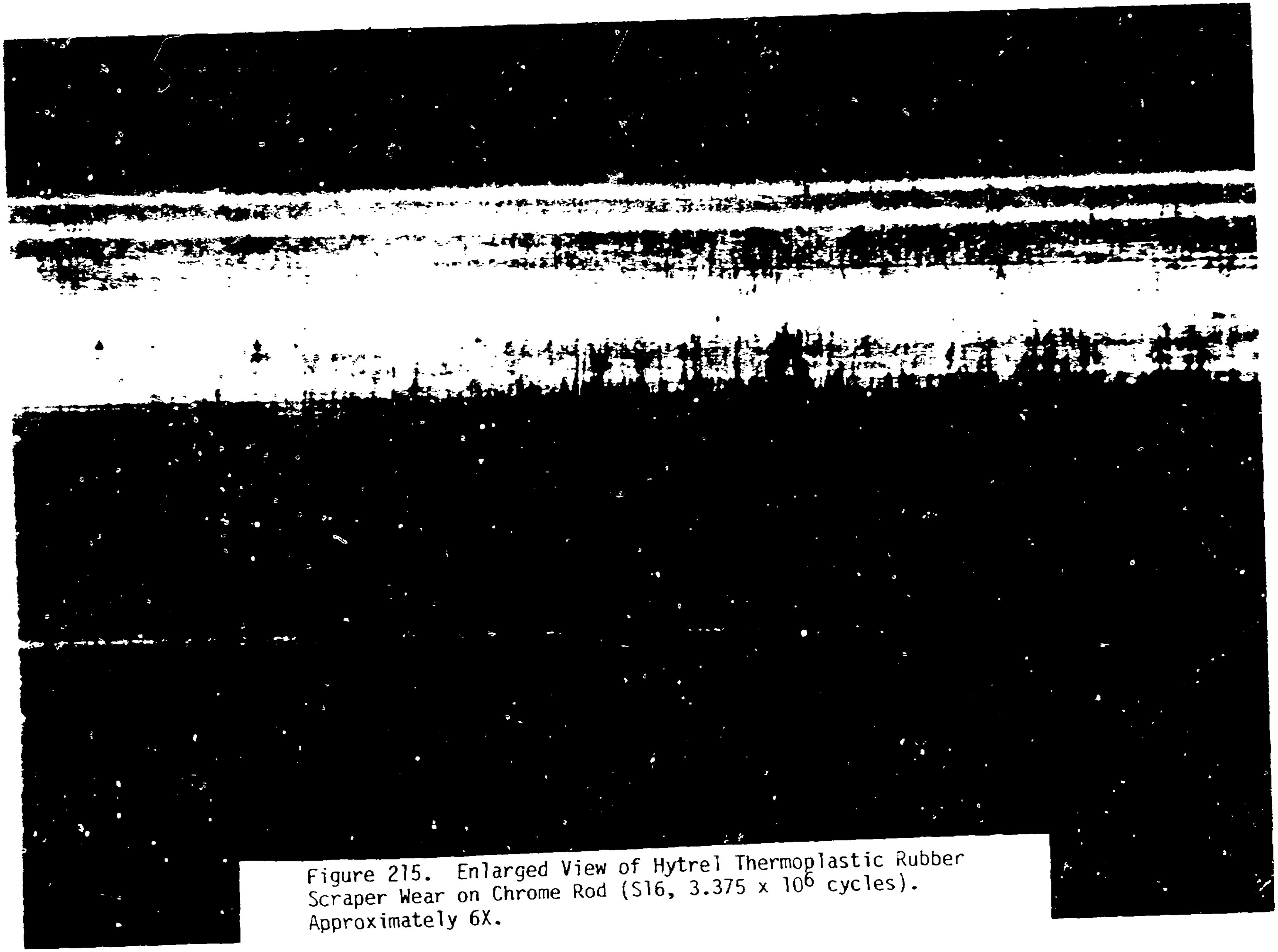


Figure 215. Enlarged View of Hytrel Thermoplastic Rubber Scraper Wear on Chrome Rod (S16, 3.375 x 10^6 cycles). Approximately 6X.

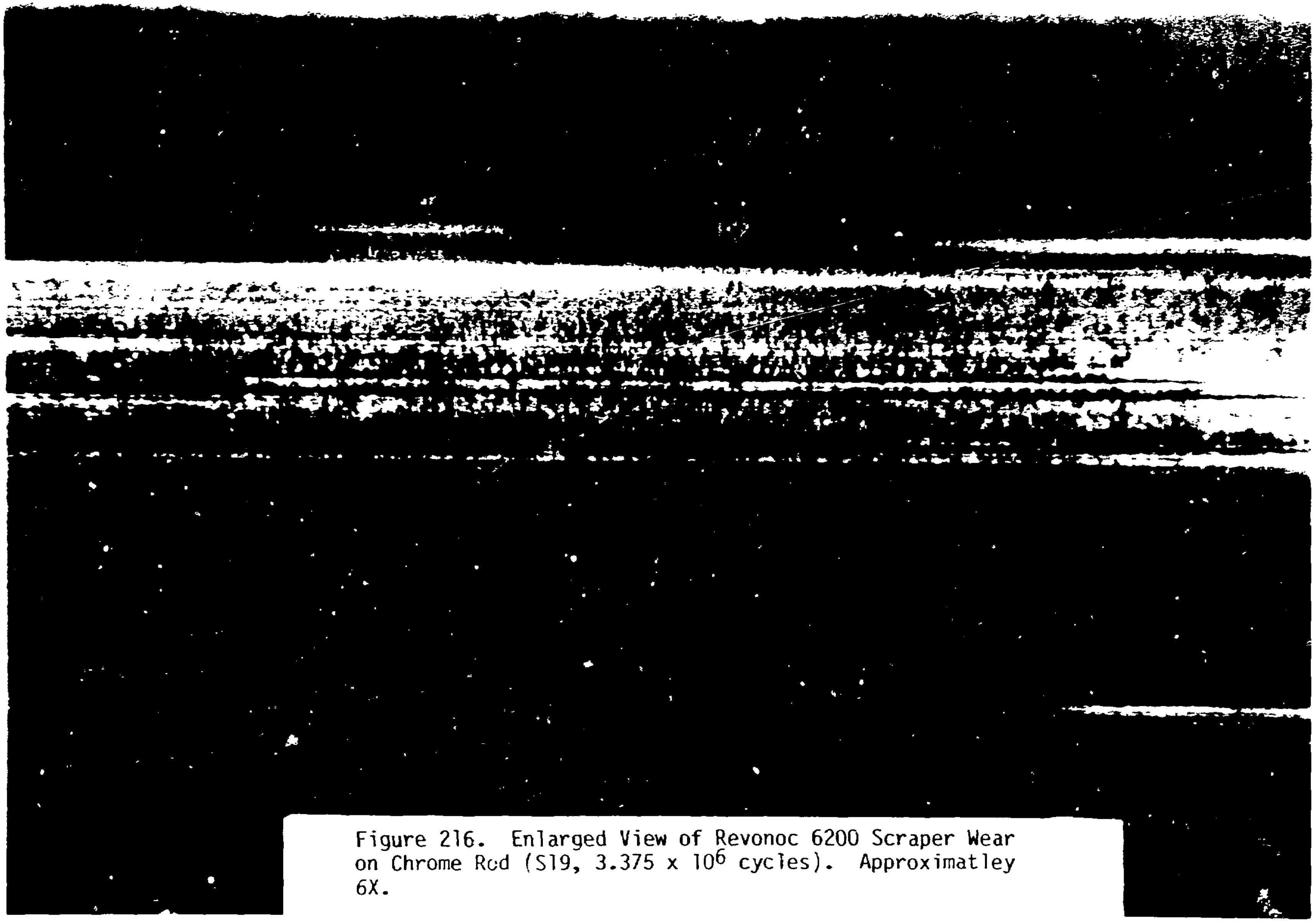


Figure 216. Enlarged View of Revonoc 6200 Scraper Wear on Chrome Rod (S19, 3.375 x 10^6 cycles). Approximatley 6X.

6.2 Scoring or Galling of Rod Chrome Plating

Localized wear through of the rod chrome plating occurred several times during the screening tests.

Rod chrome wear through occurred on chew tester assembly No. 6 at 400,979 cycles and on No. 2 at 226,077 cycles during the backup ring screening tests. The problem was corrected by careful alignment of end caps when assembled and by accurate torquing of tie rod nuts to 175 lb-in. Also a test for breakout of rod friction by pushing with hand force on the rod was made on each assembly. Using the above techniques no rod wear problems occurred during the scraper screening tests.

During the single stage rod seal screening tests cylinder assembly No. 6 developed high dynamic leakage after 686387 cycles. This assembly was an entirely different installation than for the backup and scraper tests. When examined the rod had a semicircular wear spot completely through the .0015/.0020 hard chrome plate. The bore of the 17-4 PH end cap was galled and worn at the outer edge in contact with the rod. The length of the wear pattern corresponded exactly to the rod area in contact with the end cap during the 1, 2, and 10 percent amplitude cycles of the endurance spectrum. At the time the other piston rods were examined with the system shut down. No evidence of wear was observed on other rods[1]. Since the wear problem appeared to be an isolated case it was determined to install a new rod, another end cap, and new seals and resume testing of assembly No. 6. The end cap chosen was fabricated of aluminum bronze.

The assembly was reinstalled into the test setup at 1.66×10^6 cycles with the requirement to check for rod wear once each day. Since the check for wear was being done with the system shut down, it was not determined until several days later that wear was occurring on assembly number 6 as well as the other nine assemblies. The wear was detected on the ten assemblies only when the rod was stroked at least ± 1.4 inches.

The area worn on the rods only passed under the candidate seals during the 50 and 100 percent amplitude cycling. Therefore, it was determined to finish the screening tests by retracting the rods .4 inches to a new neutral position so that a good chrome plated area contacted the end cap. The 50 and 100 percent amplitude cycling was omitted. The deletion of this portion of the endurance spectrum would reduce total rod travel under the seals by only 1.5 percent.

Upon conclusion of tests, the assembly with the aluminum bronze end cap exhibited the same wear pattern as the assemblies with the 17-4 PH end caps except the rod surface finish was much better in the wear area.

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[1] This conclusion was subsequently found to be in error. Due to the torsion bar spring loading of the cylinders the rods were pushed into the cylinders sufficiently to hide the wear areas.

Figure 217 shows the location of the wear area in relation to the end cap and seal candidate.

The source of the side loading remained unknown until the start of the two stage rod seal tests. Prior to the tests the retract end plumbing was revised on all cylinders to remove the short stiff 1/4 inch diameter tubing and to substitute looped 1/4 inch tubing. A spring scale was being used to evaluate the effectiveness of this change when it was discovered that one of the assemblies required a 16 lb side load at the rod to allow insertion of the pin in the rod end. The other assemblies were tested with side load varying from 5 to 14 lb. These side loads were due to the extend end plumbing which was comprised of 1/4 inch diameter short stiff tubing and also due to fabrication tolerances on the new retract end plumbing.

The extend end plumbing was replaced with looped 1/4 inch tubing and TFE lined hose was installed in place of the 1/2 inch diameter tubing used for extend and retract lines from the mechanical servo-valve to the distribution lines in the insulated box. All tubing was hand formed and checked for misalignment. When finished, side loads were less than or equal to 5 pounds which corresponds to the weight of the cylinder assembly.

At this point, while the source of the side loads was apparent, the number of 1 per cent stroke cycles to be accomplished encouraged another modification to the test setup. The electronics controlling the amplitude and frequency of cycling was revised to superimpose the 1, 2, and 10 percent stroke cycling onto a .05 Hz 50 percent stroke cycle ($\pm$ 1 inch amplitude). This cycling is very similar to the flight history data reviewed to derive the endurance spectrum. The data showed that as a surface made a major displacement there were many random minute displacements from the nominal position of the surface, undetectable to the eye but recorded by the instrumentation.

In subsequent Long Life testing, the rods were inspected frequently with no recurrence of the rod wear problem.

During the additional screening tests, rod scoring occurred three times on Chew Tester Assembly No. 6. After each failure, the rod was replaced, the end cap bore was refinished to an 8 - 16 rms surface and the assembly was reassembled with a requirement that the rod could be pushed by hand after all torquing was completed. These actions did not eliminate the problem and the assembly was removed from test after 1.76×10^6 cycles. All other assemblies completed 3.375×10^6 cycles with no problems. Figure 190 shows the damage to the chrome plate as a result of scoring. The damaged area is denoted by arrows.

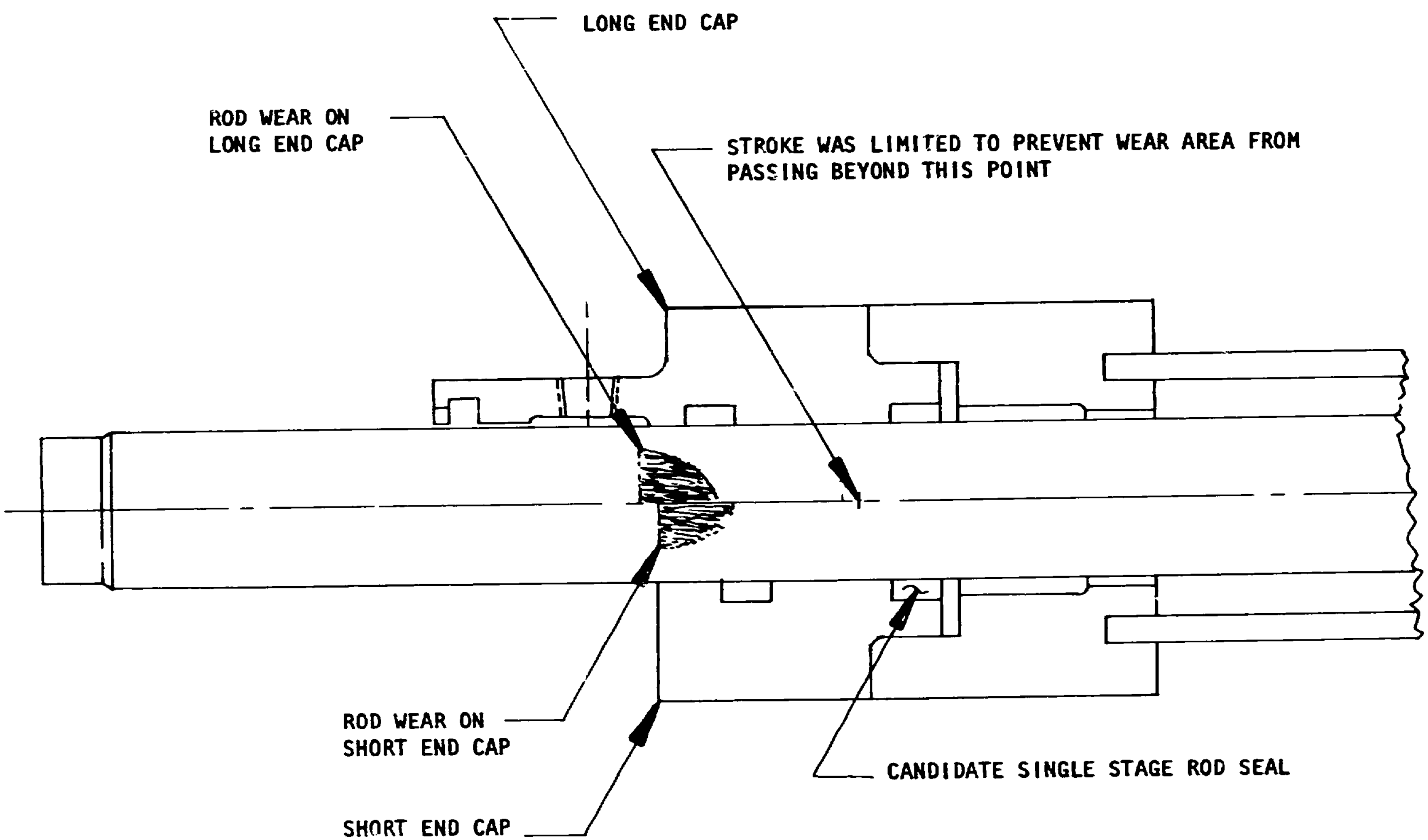


Figure 217. Location of Rod Wear in Relation to Candidate Seals on Single Stage Rod Seal Screening Tests.

7. DISCUSSION OF LEAKAGE COLLECTION

Throughout the screening tests the collection of leakage from each seal was planned for by the installation of a clean plastic bottle connected by a 1/4 inch diameter aluminum tube to each end cap. In most installations the tube was connected by fittings to a port on the under side of the end cap just outboard of the candidate seal. In a few instances where no port was available due to the number of seals installed in the end cap, the tube was attached to the end of the end cap in a manner to collect any fluid dripping from the end of the end cap. In the course of testing, it was discovered that other factors affected leakage collection.

In the backup ring screening tests it was necessary to raise the ambient temperature in the insulated box to 280 - 290°F in order to achieve 275°F oil temperature at the test housings. The box was heated by blowing heated shop air into the box thru a tube with drilled holes equally spaced along its length to distribute the air. It was discovered that leakage would not always accumulate at the place provided but tended to accumulate on the underside of the rod. The hot air evaporated the volatile components of the oil leaving a black viscous residue. Subsequently, a special room temperature ambient, 1000 cycle leakage test was performed on the backup ring candidates to be able to make judgements on backup ring candidate leakage.

During the scraper test, backup candidates were tested on the end of the test housing opposite the scraper test. A M83461/1-214 O-ring was installed as a wiper outboard of each backup ring candidate installation. Leakage was collected with no problems. During the single stage rod seal tests, the wiper O-ring was installed outboard of each seal candidate and once again leakage collection was positive and accurate.

During the two stage rod seal tests, no groove was available for a wiper and all leakage tended to accumulate on the underside of the piston rods and to become a black viscous residue. The only judgement which can be made about two stage rod seal leakage was based on wiping the underside of the rod for each candidate. If the rod had an oil film or collection of residue, it can only be stated that leakage occurred. Some of the rods so wiped were dry, with no oil film or residue. It is assumed these candidates did not leak.

These difficulties stress the importance of the use of a wiper outboard of the candidate to be sure all leakage accumulates in the collector provided. The wiper should be an O-ring so that rod surface finish is not affected. The only exception to the use of a wiper O-ring is when the effect of air aging of the candidate during the test is a factor.

8. DESCRIPTION OF TEST SET UP

All tests in this program were conducted on one test system which was capable of being converted into two configurations.

The first configuration used eight cylinders configured as chew testers. The extend and retract ports of all cylinders were interconnected. The cylinders were driven by an electrohydraulic actuator. The electrohydraulic servoactuator was controlled by a wave generator and amplifier to allow consistent reproduction of the mechanical endurance spectrum.

The second configuration used ten single ended actuators which were loaded externally by a torsion bar for each actuator. The actuators were controlled by an aircraft type mechanical input servovalve operated by an electrohydraulic servoactuator.

8.1 Test Articles.

8.1.1 Chew Testers. All screening tests on scrapers and backup rings were conducted in chew testers. Each chew tester assembly consisted of a double ended commercial actuator with Vought designed end caps substituted. The actuator was made to function as a chew tester by connecting extend and retract ports together. Figure 218 shows this assembly.

8.1.2 Sand and Dust Application. The device used to apply standard AC coarse test dust to the cycling rods during the scraper screening tests is depicted in Figure 219 which shows a chain driven rotating cannister with two angled internal blades. As the cannister rotated, each blade picked up contaminant and distributed it along the top of the piston rod. The test set up operated eight cannisters simultaneously by an electromechanical drive with infinitely variable transmission. All cannisters contained 9 cc of standard AC coarse test dust and were rotated at 20 $\pm$ 3 rpm. The test dust was vacuumed out of the cannisters and replaced at regular intervals to minimize the effect of oil soaking into the contaminant. Figure 220 shows the cannisters and chain drive.

The rotating cannister used to apply the standard AC coarse contaminant worked very well. While the volume of contaminant applied to the rod per unit of time is much greater than would be experienced on an aircraft, the concept still is a compact, low cost way of uniform application. Problems encountered with the design used were minor. The 1.25 inch diameter access hole used to vacuum out used contaminant required excessive time to vacuum out all of the contaminant. An improvement would be to design the cannister so that it could be easily removed from the end cap for cleaning and reservicing with fresh contaminant. The cannister housing was a deep drawn .050 wall aluminum can commercially available. The cans were easily bent in the course of assembling the cannister. An alternate material which would be

satisfactory is polyacrylic tubing. A full size model of the cannister was made of acrylic plastic tubing of 3.00 OD and .125 wall which could have worked satisfactorily in the test set up. The idea of removing oil contaminated contaminant every two test days was satisfactory. If time to remove the contaminant is minimized, daily rcplacement of contaminant would be an improvement.

8.1.3 Test Cylinders. All screening tests on single and two stage rod seals as well as the Long Life Tests, were conducted using single ended commerical actuators. The actuators were modified by the substitution of Vought designed end caps which allowed up to two rod seals and a scraper to be installed. Figure 221 shows the details of the test cylinders.

8.2 Mechanical Test System

The mechanical test system provides a fixture for the mounting and cycling of the chew testers and for mounting, loading, and cycling of the test cylinders. Figure 222 is a photograph of the fixture configured for the scraper screening tests. Figure 223 is a photograph of the fixture configured for operation of test cylinders with torsion bar loading. Important features of this concept are:

- Same stroke on each test article.
- Installation of 1 to 10 test articles.
- Removal of a single test article, with continued cycling on other test articles.
- Chew testers or test cylinders with minimum modification.
- Single servo actuator can cycle all chew testers.

The load transfer component of the test fixture is a torque tube bellcrank consisting of a tube with bell cranks welded on at equal intervals. End bell cranks are 180° opposite all others and provide a pivot point for the torque tube. The "A" members on each side support the torque tube and are grounded to the base of the fixture. Test articles are also grounded to the base of the fixture. The assembly provides the stiffness required to impose the same stroke on each test article.

8.2.1 Chew Tester Installation. The test fixture allowed simultaneous cycling of eight chew testers. The electro-hydraulic servo-actuator driver had a 5000 lb. capacity. The electrohydraulic servo-actuator is designed for high frequency dytnamic testing involving sinusoidal oscillations from 0.1 to 100 Hz. The servo-actuator was chosen over a solenoid valve controlled actuator because it provided for:

- A positive feedback device.
- A method where the stroke and frequency may be raised.
- A source of sinusoidal cycling.

8.2.2 Test Cylinder Installation. The test fixture imposed the same stroke on each cylinder. The ten cylinders were controlled by a single flight control type mechanical servo-valve. The mechanical servo-valve was driven by the same type servo-actuator used for the chew testers. The mechanical servo-valve was chosen because it can withstand constant operation at +275°F. Experience has shown that use of electro-hydraulic servo-valves in test systems for extended periods at +275°F results in loss of test time due to failure of the electro-hydraulic servo-valves. The mechanical servo-valve consists only of a sleeve and slider with two dynamic seals and eight static seals.

8.2.3 Control of Stroke. Servo controlled inputs were used so that the chew testers and the test cylinders were subjected to uniform repeatable testing. A single servo-actuator operated all chew tester rods. The servo-actuator has an integral LVDT for position feedback. The output was monitored with a position transducer.

8.2.4 Test Cylinder Loading. Each test cylinder, with a 1-1/2 inch bore and 1-inch rod has a thrust of 2768 lbs. when retracting assuming 3000 psi to retract with a 100 psi back pressure on the extend side. Each test cylinder was subjected to loading proportional to stroke. The method of loading was a torsion spring for each cylinder. Several loading methods was considered. They were:

- A single large spring for loading of all test cylinders.
- Hydraulic cylinders.
- Individual spring load for each test cylinder.

Spring loading was chosen over hydraulic because less maintenance is required. A single spring was ruled out because the individual test cylinder loading would vary if a test cylinder had to be removed while a seal failure was being analyzed. This reduces the choices down to a coiled spring or a torsion spring for each test cylinder. The torsion spring were chosen because they are reasonably small for the load levels required and they could be fabricated in-house. Figure 224 is a photograph of the installation of the test cylinders with external loading. The same test fixture used for the chew testers is modified for the test cylinders. Modifications required were:

- Differences in grounding the test cylinders
- Removal of the electro-hydraulic servo-actuator
- Addition and grounding of the ten load springs
- Addition of mechanical servo-valve and servo-actuator
- Rotation of entire fixture 90° in test cell

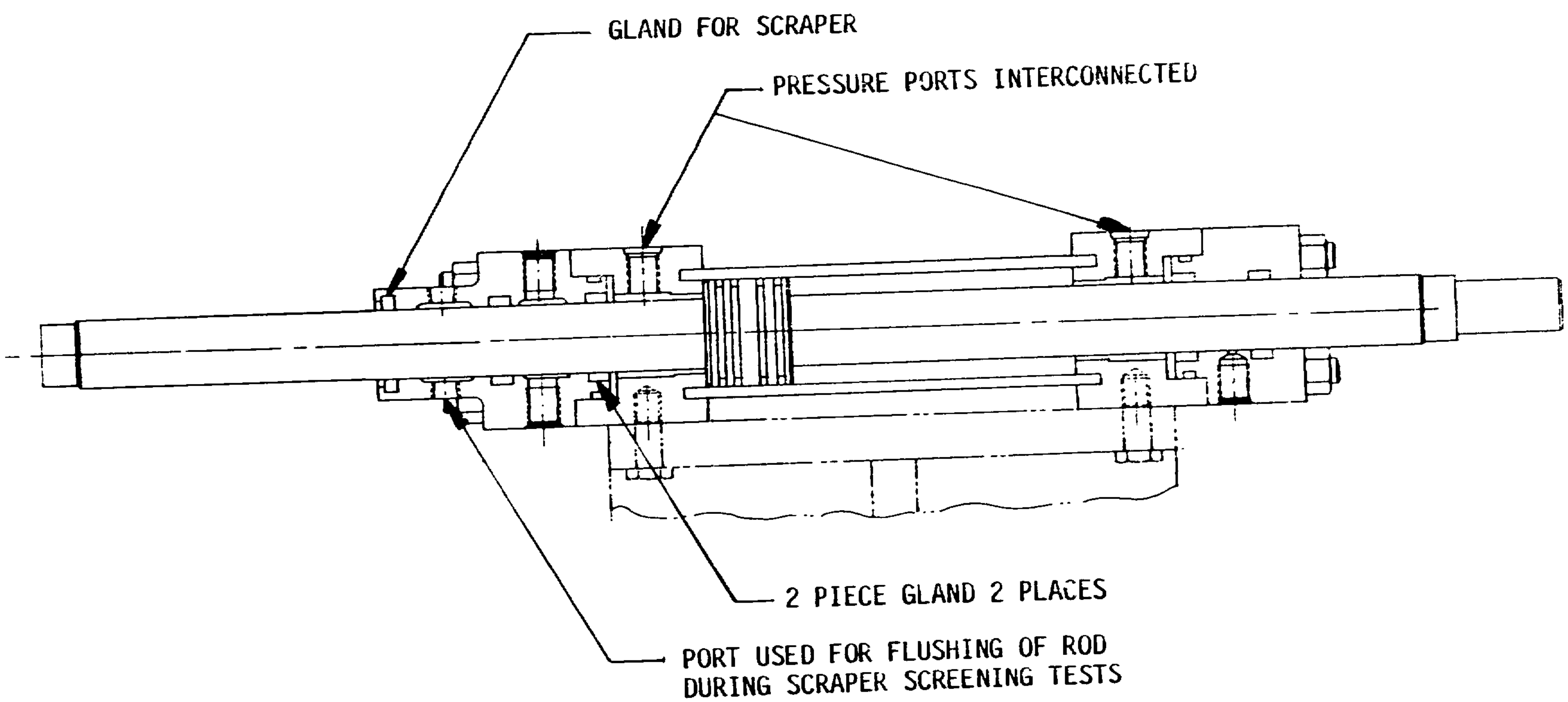
8.2.5 Temperature Control. The test articles were in a box fabricated from plywood faced fiberglass insulation board. Fluid to the test articles passed through a heat exchanger using hot air from a supplemental heater with thermostat control.

The test articles were cooled by use of liquid carbon dioxide released through an expansion valve. The rate of flow was controlled to lower the temperature and stabilize within limits for leakage tests at low temperature.

Ambient temperature in the box was controlled by use of hot air exhausted from a supplemental heater with thermostatic control. All temperatures were monitored on a multichannel recorder.

8.3 Test System Hydraulic Supply

Two independent hydraulic systems were utilized. One system exclusively powered the electro-hydraulic servo-actuator. The other system was subject to environmental temperatures required of the test system and pressurized the chew testers and the test cylinders. Figure 225 is a schematic showing the system for operation of the servo-actuator and the system for the chew testers and test cylinders. Thermocouples and pressure transducers allowed monitoring and adjustment of temperature and pressure to assure uniform test conditions for all candidates. The initial screening tests of backup rings and scrapers had a single hydraulic supply system. It was determined in the course of testing that the heat exchangers were not capable of heating the oil to +275°F without running above 275°F in the industrial pumping system used. The system was modified to two independent circuits. The high temperature loop was powered by a pressure compensated variable displacement aircraft pump which allowed up to 275°F in its case drain circuit. This allowed limitation of temperature of the industrial pump circuit to 180°F.



ORTMAN 3TH SERIES CYLINDER
4-inch stroke
.997/.998 Dia chrome plated rod

Figure 218. Chew Tester Assembly Used for Backup and Scraper Screening Tests

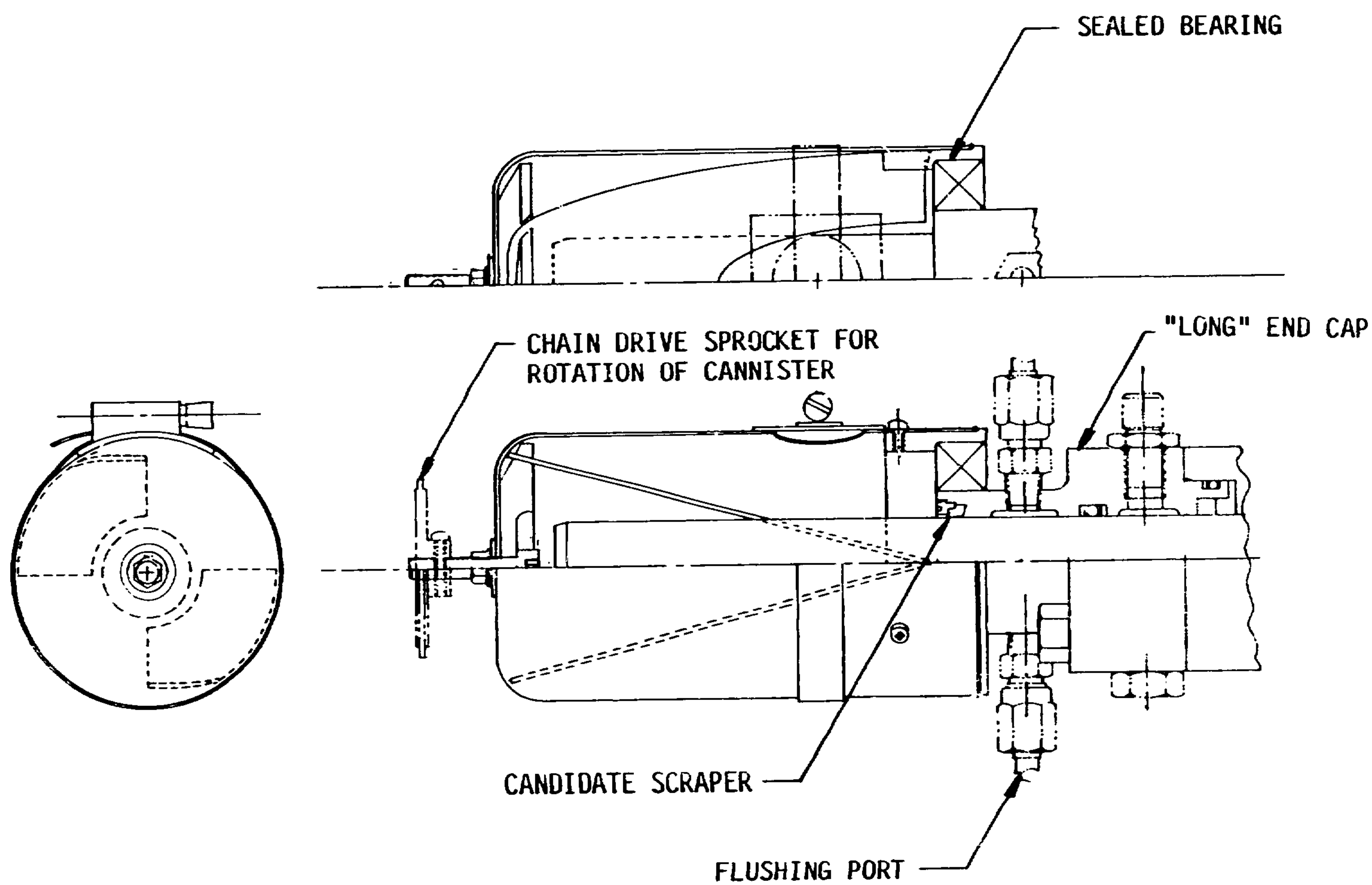


Figure 219. Contamination Cannister Installation Used for Scraper Screening Tests.

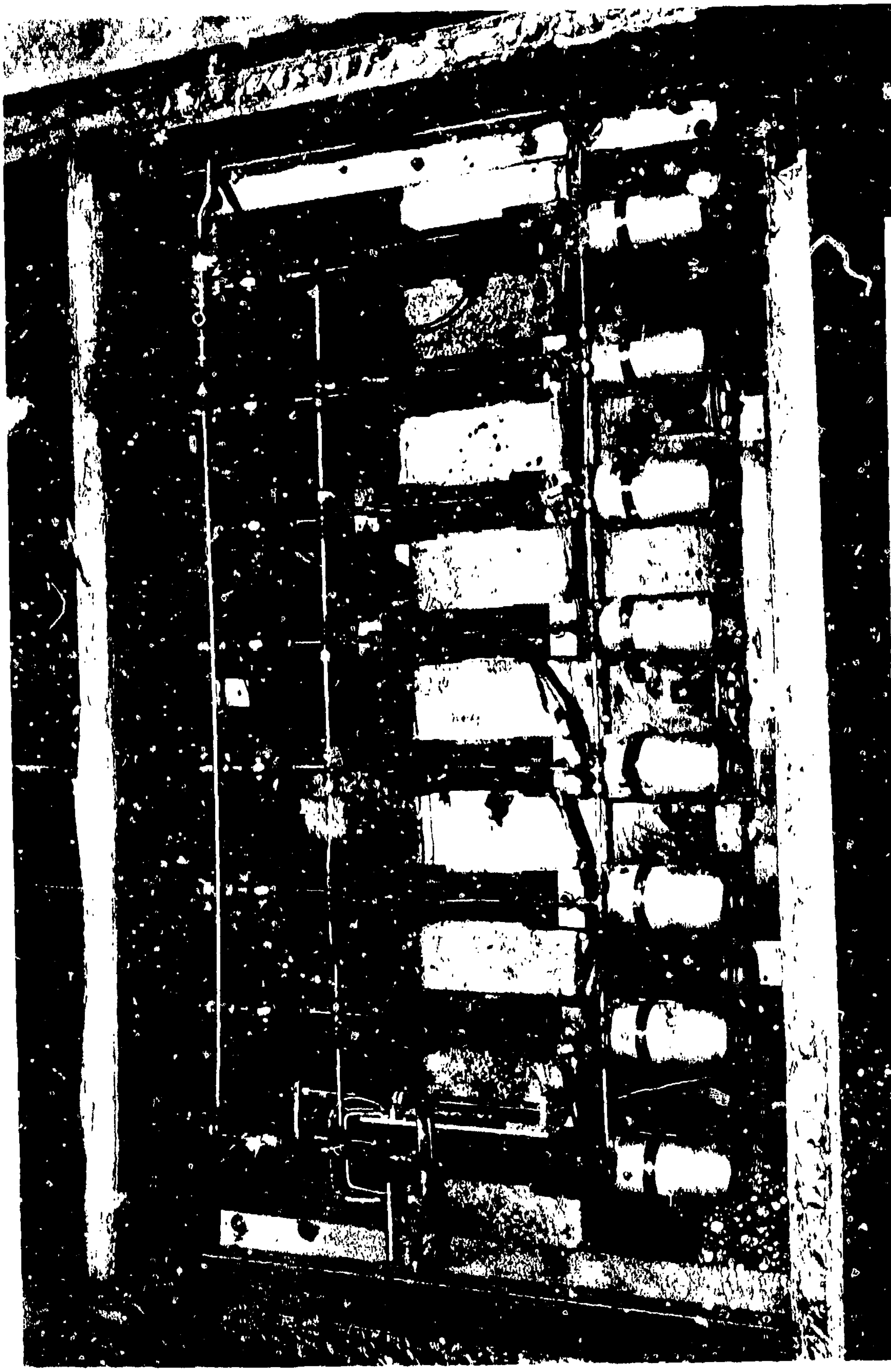


Figure 220. Scraper Screening Test Setup. Same Setup was used for Additional Screening Tests and for Backup Screening Tests (with contamination cannisters removed).

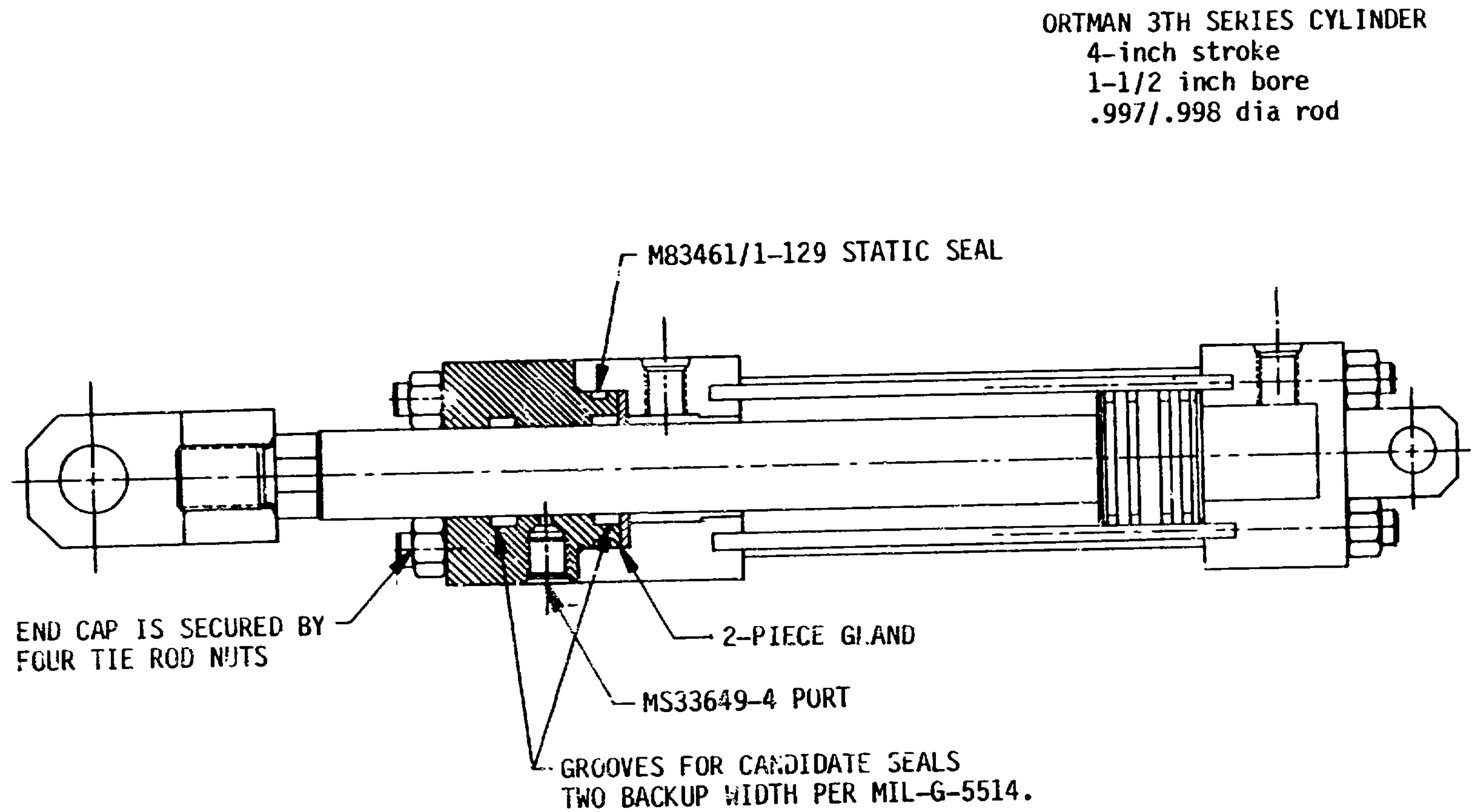


Figure 221. Test Cylinder Used for Single and Two Stage Rod Seal Screening Tests and for Long Life Test

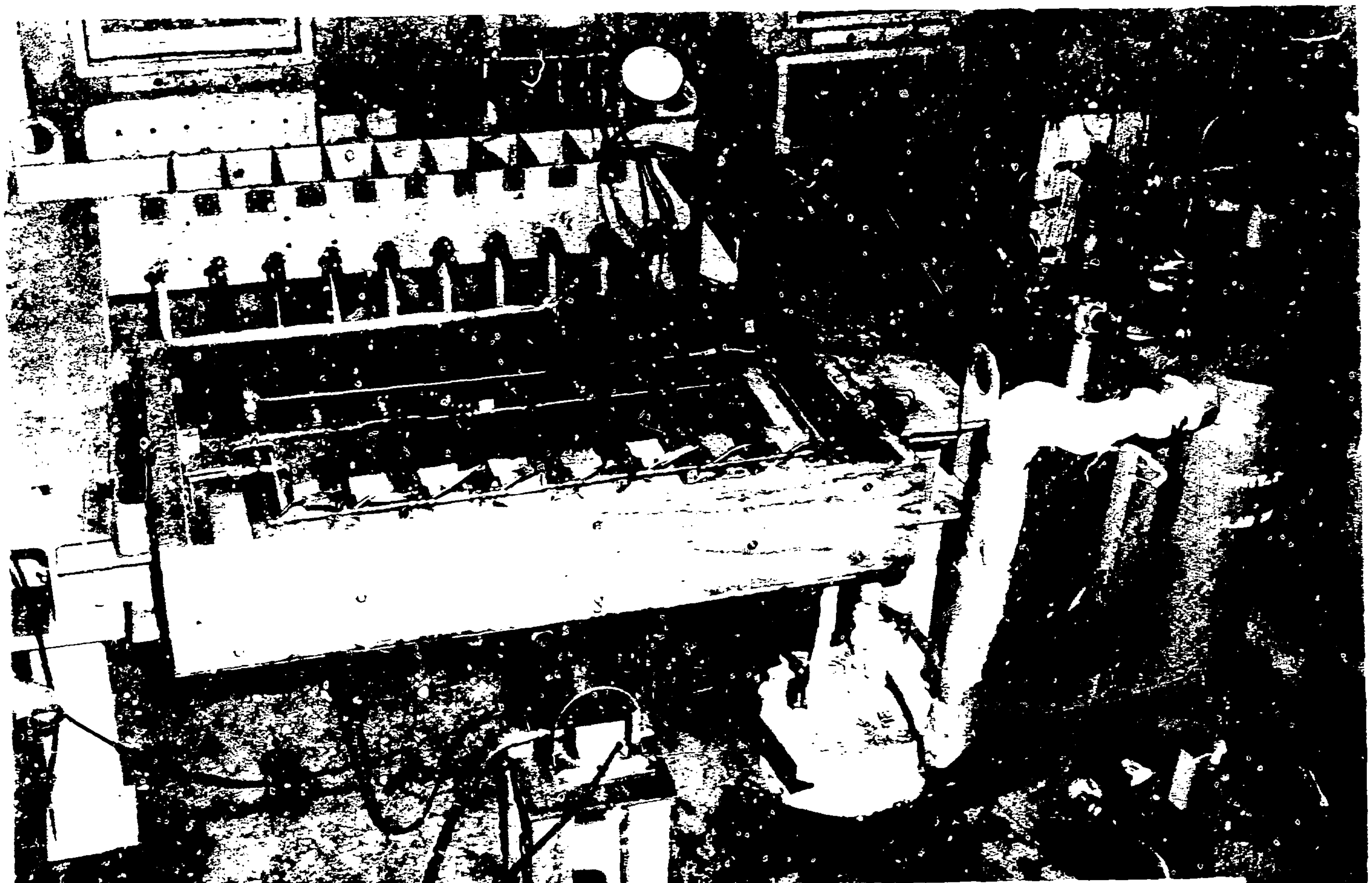


Figure 222. General view of Test Setup. Test cylinders may be attached to lugs (square, black objects) at top of photograph.

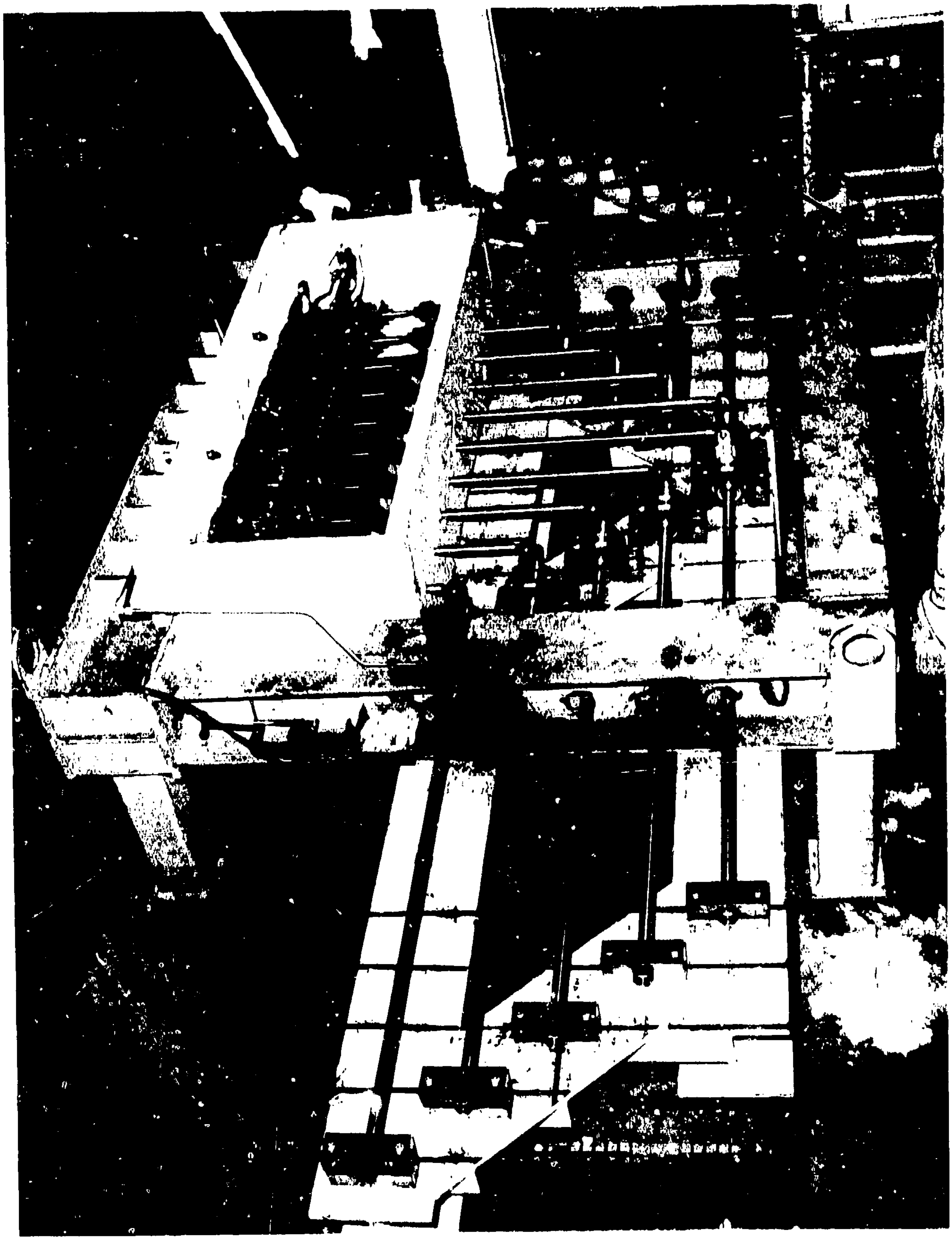


Figure 223. Test Setup Used for Single Stage Rod Seal, Two Stage Rod Seal; and Long Life Tests.

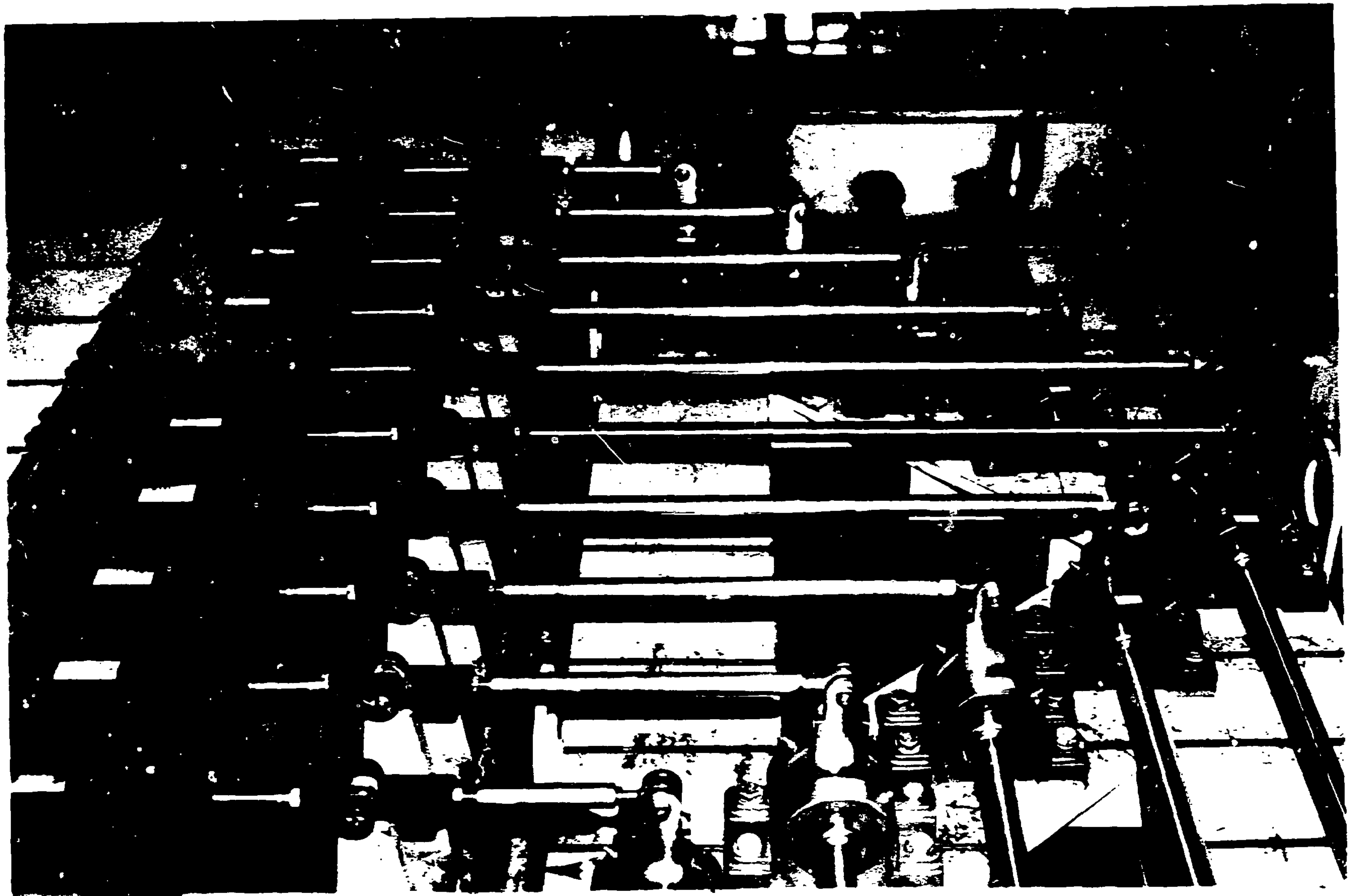


Figure 224. Details of Torsion Bar Loading on Test Cylinders. Torque tube (arrow) assured same stroke and loading for each cylinder.

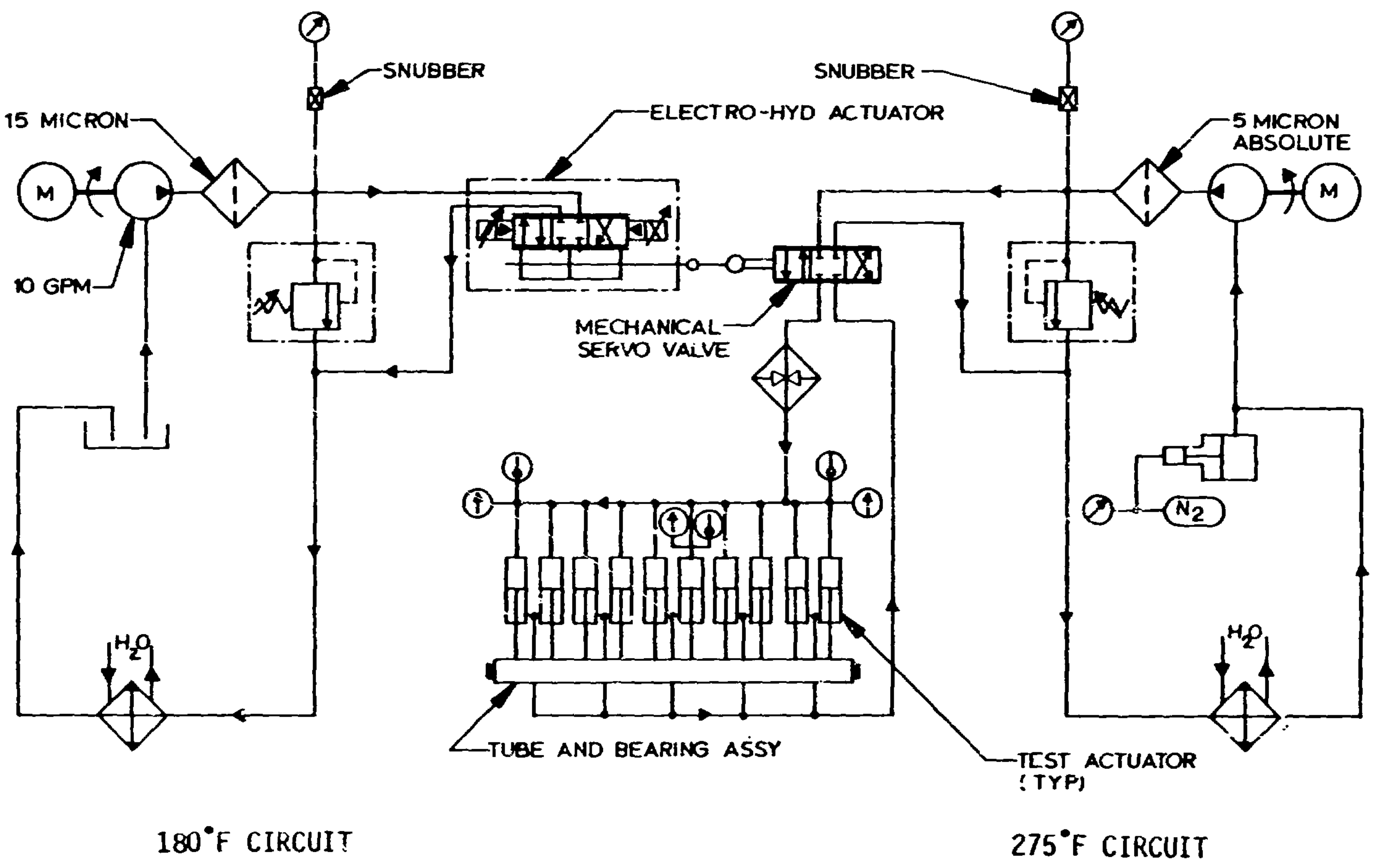


Figure 225. Test System Schematic. Single-stage rod seal, two-stage rod seal, and Long Life Test configuration shown

9. TEST PROCEDURES

9.1 Backup Ring Screening Test.

9.1.1 Test Setup. Install candidates into end caps which are assembled into chew tester housings. Use an M83461/1-214 O-ring with each back-up candidate. Install the chew testers into the test setup.

9.1.2 Daily Procedure.

a. Check and record the static leakage from each candidate.

b. Install collectors for dynamic leakage.

c. Circulate ambient temperature fluid through chew tester housing at a low rate for 5 minutes.

d. Begin cycling when fluid temperature is 220 ±5°F.

e. Cycle the chew test rods in accordance with the spectrum below which is counted as 1 block.

PERCENT TOTAL STROKE	STROKE - IN	PRESSURE	NO. OF CYCLES
1	± .02	3000	154616
2	± .04	3000	14949
10	± .20	3000	1068
50	± 1.00	3000	170
100	± 2.00	3000	42
			170845

f. Apply impulse pressure of 0-4500 psig at a rate of 30 ±5 cycles/sec for 4545 cycles upon completion of each block.

g. Continue until all candidates fail or twenty two blocks are accomplished which ever occurs first.

h. Conduct post-test evaluation.

9.1.3 Rod Bushing Material Screening Tests.

a. Assemble one chew tester assembly with an aluminum bronze bushing end cap on the lug end and a standard 17-4 PH end cap on the rod end.

b. Install an M83461/1-214 O-ring and an MS28774-214 backup (Candidate B1) as a single stage seal in the aluminum bronze end cap.

c. Test simultaneously with backup screening test.

d. Conduct post test evaluation.

9.2 Scraper Screening Test

9.2.1 Test Setup. Rework end caps to accept contaminant application system shown on Figure 219.

Install candidate scrapers into 17-4 PH end caps and assemble into chew tester assemblies.

Install chew tester assemblies into test system shown on Figure 220 with contaminant application system installed.

Place 9 cc of AC coarse test dust into contaminant containers.

9.2.2 Daily Procedure. The daily procedure will be as follows except particle counts are to be conducted every three days.

a. Particle count for each scraper candidate: Flow clean MIL-H-5606 through the top and bottom ports of the end cap into a clean container until a 175 ml sample is collected. Forward the container to the lab for a contaminant particle count. The data should be identified with date, identification number of candidate, and number of cycles on scraper.

b. Remove the access cover on the contaminant container and vacuum out old contaminant. Replace with 9 cc of fresh AC coarse test dust.

c. Circulate 275 5°F fluid through chew tester housing at .25 GPM. Apply 2 drops/hour of MIL-H-5606 oil at port between scraper and rod seal. Raise ambient air in environmental box to 170 +20 -0°F.

d. Rotate drive system at 25 ±3 rpm.

e. Cycle the chew test rods in accordance with the spectrum below which constitutes 1 block.

PERCENT TOTAL STROKE	STROKES - IN	NO. OF CYCLES
1	± .02	124827
2	± .04	12069
10	± .20	862
50	± 1.00	138
100	± 2.00	34
		137930

f. Continue until all candidates fail or eighteen blocks, are accomplished whichever occurs first.

9.3 Single Stage Rod Seal Screening Test.

9.3.1 Test Setup. The test jig and hydraulic system will be set up to accept actuators which are loaded by torsion bars. The actuators will be extended and retracted by a mechanical servo-valve which is driven by a servo-actuator.

9.3.2 Daily Procedure. Each morning, record the accumulated leakage for each candidate, along with the date, and number of cycles completed.

Begin cycling, raise fluid temperature to +275 ±5°F.

Cycle the test cylinders using the following spectrum which constitutes 1 block.

PERCENT TOTAL STROKE	STROKES - IN	NO. OF CYCLES
1	± .02	156034
2	± .04	15086
10	± .20	1078
50	± 1.00	172
100	± 2.00	43
		172413

9.3.3 Low Temperature

Each five days cool the test cylinders to -65 +5/-0°F and stabilize. Apply 5 +5/-0 psig to retract port on cylinder with piston retracted. Monitor external leakage for one hour in separate clean containers. (Set containers used for dynamic leakage aside until low temperature tests are complete).

While fluid temperature is at -65°F, slowly cycle test cylinders through five complete cycles with pressure build-up to 3000 +100/-0 psi at the end of each stroke. At least the first cycle shall be made with fluid at the specified temperature. Monitor external leakage and record.

Continue until failure of all candidates or completion of 26 blocks are accomplished whichever occurs first.

Perform post-test evaluation.

9.4 Two Stage Rod Seal Screening Test

9.4.1 Test Setup. The test set up will be the same as used for the single stage rod seal screening tests. Actuators will be used which are loaded by torsion bars. The actuators will be extended and retracted by a mechanical servo-valve which is driven by a servo-actuator.

9.4.2 Test Spectrum. The test spectrum derived for this program will be used except that the 1, 2, and 10 percent strokes will be superimposed upon the 50 percent (± 1-inch) stroke.

9.4.3 Daily Procedure. Each day, the test procedure will be as follows:

a. Check and record the static leakage from each candidate.

b. Replace containers for dynamic leakage collection.

c. Turn on heaters to oil heat exchanger and to insulated box.

d. Begin cycling. As air and oil heat up, stabilize oil temperature at 250 to 275°F. Stabilize air temperature in box at 170 to 190°F.

e. Each day the cycling is to be performed in the following sequence which constitutes one block:

PERCENT STROKE	NUMBER OF CYCLES				RATE
1	104479				11 Hz
2		10097			4
10			728		1
50	476	126	61		0.05
100				29	0.10
	104955	10223	789	29	

If this sequence is completed prior to the end of the work day it will be started again.

f. At the conclusion of the work day, set aside the dynamic leakage containers. Install clean, dry containers for overnight static leakage collection. Apply a 3 foot head of oil to the retract line of the test cylinders.

9.4.4 Low Temperature Test. Once a week, in the morning, perform a low temperature leakage test as follows:

a. Check and record the static leakage from each candidate.

b. Install clean, dry containers for low temperature static leakage.

c. Apply 5 ±1 psi to the extend and retract lines.

d. Reduce oil temperature to -65 +0/-5°F and stabilize for 15 minutes.

e. Maintain test cylinders at -65°F for 1 hour, then cycle ±1-inch for 5 cycles.

f. Remove leakage containers and record leakage.

g. Continue at step 9.4.3.b.

9.4.5 Length of Test. The procedure of paragraphs 9.4.3 and 9.4.4 will be repeated until 28 blocks have been completed.

9.5 Long Life Test

9.5.1 Test Setup. The test set up will be the same as used for the two stage rod seal screening tests. Actuators will be used which are loaded by torsion bars. The actuators will be extended and retracted by a mechanical servo-valve.

9.5.2 Daily Procedure. Each day, the test procedure will be as follows:

a. Check and record the static leakage from each candidate.

b. Replace containers for dynamic leakage collection.

c. Turn on heaters to oil heat exchanger and to insulated box.

d. Begin cycling. As air and oil heat up, stabilize oil temperature at 250 to 275°F. Stabilize air temperature in box at 170 to 190°F.

e. Each day the cycling is to be performed in the following sequence:

PERCENT STROKE	NUMBER OF CYCLES				RATE
1	104479				11 Hz
2		10097			4
10			728		1
50	476	126	61		0.05
100				29	0.10
	104955	10223	789	29	

If this sequence is completed prior to the end of the work day it will be started again.

f. At the conclusion of the work day, set aside the dynamic leakage containers. Install clean, dry containers for overnight static leakage collection. Apply a 3 foot head of oil to the retract line of the test cylinders.

9.5.3 Low Temperature Test. Once a week, in the morning, perform a low temperature leakage test as follows:

a. Check and record the static leakage from each candidate.

b. Install clean, dry containers for low temperature static leakage.

c. Apply 5 ±1 psi to the extend and retract lines.

d. Reduce oil temperature to -65 +0/-5 degrees F and stabilize for 15 minutes.

e. Maintain test cylinders at -65 degrees F. for 1 hour, then cycle ±1-inch for 5 cycles.

f. Remove leakage containers and record leakage.

g. Continue at step 9.5.2.b.

9.5.4 Length of Test. The procedure of paragraphs 9.5.2 and 9.5.3 will be repeated until 13.2×10^6 cycles have been completed.

9.5.5 Failure of a Candidate. If a candidate fails during the first half of the Long Life Test, the nature of the failure will be determined. If the failure is due to installation method, abnormal wear of the rod, or is clearly not the fault of the seal, a new similar candidate will be installed with a new rod as required and restarted in the test. If the failure is within the operating charactersitics of the seal, a new candidate will be considered for inclusion in the test program. Verbal concurrence with the project engineer at the Aero Propulsion Laboratory will be made on any new candidates to be considred for installation. If the failure occurs during the last half of the Long Life Tests, the option of disconnecting the failed cylinder from the test will be considered based upon the amount of rod wear experienced, availability of spare rods, and how far into the last half of testing the failure occurred.

9.6 Additional Screening Tests

9.6.1 Test Setup. The test set up will be the same as used for the scraper screening tests. Chew testers will be used which are extended and retracted by a servo-actuator.

9.6.2 Test Spectrum. The test spectrum derived for this program will be used except that the 1, 2, and 10 percent strokes will be superimposed upon the 50 percent (±1-inch) stroke.

9.6.3 Daily Procedure

a. Replace static leakage containers 10 places with dynamic leakage containers.

b. Measure and record static leakage for each assembly. (Assemblies No. 1 and No. 8 have "lug" end and "rod" end leakage).

c. Apply 2 drops/running hour MIL-H-5606 at contamination flushing tube (6 hours/day = 12 drops).

d. Turn on heat.

e. Turn on cannister drive (17-23 RPM).

f. Start cycling with constant 3000 psig on test assemblies.

g. Stabilize temperatures as follows:
Inlet oil 265 - 275°F
Box ambient 170 - 190°F

h. Conduct cycling in blocks as follows:

PERCENT STROKE	NUMBER OF CYCLES				RATE
1	104940				11 Hz
2		10320			4
10			780		1
50	477	129	39		0.04
100				30	0.10
	105417	10449	819	30	

Cycles = 116715/Block

9.6.4 At the End of Each Working Day:

a. Apply 5000 cycles 0 - 4500 psig impulse pressure.

b. Remove dynamic leakage containers - do not measure dynamic leakage, just accumulate in same container for each assembly until end of tests.

c. Reinstall static clean leakage container 10 places.

9.6.5 Every Other Day - Morning:

a. Vacuum test dust out of containers.

b. Flush cavity between scraper and rod seal with 150 ml of filtered PD680.

c. Collect PD680 in new clean bottle (6 oz size).

d. Identify each bottle with date and assembly number.

e. Place 9cc of AC coarse test dust in each container.

f. Go to paragraph 9.6.3.

10. CONCLUSIONS

10.1 Fly-By-Wire Control System Study

The study verified that fly-by-wire control systems result in very high numbers of small amplitude cycles imposed on flight control actuators.

The derived endurance spectrum for a 4000 hour aircraft is as follows:

Percent Stroke	FBW Total Cycles
1.0	3.62×10^7
2.0	3.50×10^6
10.0	2.50×10^5
50.0	4.00×10^4
100.0	1.00×10^4
	40.00×10^6

In the flight test data reviewed, the small amplitude cycles were displacements from a larger amplitude cycle.

10.2 Backup Rings

The most significant single factor for O-ring protection by a backup ring is to have a triangular or trapezoidal shape. This factor was evaluated in materials as soft as unfilled TFE to as hard as acetal resin and polyimide. The trapezoid shaped Shamban "Delta" backup was evaluated in 7 samples, four materials (Candidates B3, B23, B30, B35). No O-ring damage occurred in 6 of 7 samples. A heavy duty trapezoid shape was evaluated in 3 samples, 3 materials (Candidates B27, B28, B29). O-ring condition was good for two samples. The sample in Vespel SP-21 failed due to nibbling and extrusion after completing 1.5 million cycles of the endurance spectrum. The triangular shape was evaluated in 2 samples of unfilled TFE in (Candidate B8). Both samples gave excellent O-ring protection.

No single rectangular shape protected the O-ring consistently. In 26 installations of MS28775-214 backups (Candidate B1), seven allowed the O-ring to deteriorate to a fair or poor condition; 8 failed catastrophically. MS27595-214 (Candidate B9) was tested in two samples, O-ring condition was excellent with one, fair with the other.

The second most significant factor is material. Extremely hard, low cold flow materials did not provide any better protection than unfilled TFE when tested in a rectangular shape (Candidate B15, B25, B26, B31, B33). Materials which were in the low to moderate hardness, moderate

cold flow gave better protection (Candidate B1, B2, B9, B24). Any specification for backup ring materials should require determination of Rockwell hardness consistently using the "R" scale and cold flow or deformation for 1000 hours at 3000 psi compressive stress and 212°F or higher. Based on the limited data available, a Rockwell hardness of R80 to R90 is desirable with deformation of less than 48 percent.

The third most significant improvement is to stage backups of similar or same material. Candidate B22, a two stage backup of rectangular shaped Revonoc 18158 material, gave excellent O-ring protection in two samples, fair in another. In two cases (Candidate B19 and B6) where a very hard material backup was outboard and a softer material backup was inboard, the O-ring was not protected. Double thickness or square backups (Candidates B5, B17) did not provide O-ring protection.

An initial interference fit with the rod equal to the thermal expansion from 70°F to maximum operating temperature is desirable, but will not guarantee O-ring protection. Backup wear or yielding of the material due to the amount of interference fit will eliminate the benefit of the interference fit.

O-ring condition alone does not determine leakage performance. As shown in Table 8, there were a number of samples (B20, B22, B3, B35, B23) where the O-ring was in excellent condition upon completion of test but some (extremely low) leakage did occur. The same table shows other candidates which allowed nibbling and extrusion of the O-ring to the "fair" or "poor" condition which had zero leakage recorded (Candidates B25, B16, B19).

Impulse testing should be a part of any backup ring or seal tests. The nine MS28774-214 backup installations in the initial scraper screening tests all survived the test with O-ring condition deteriorating only to the good or fair categories. In fourteen MS28774-214 installations in the additional scraper screening tests, there were eight catastrophic failures caused by nibbling and extrusion of the O-ring and backups. The initial scraper screening tests did not have impulse pressure applied to the rod seals. The additional scraper screening tests applied 5000 cycles of 0 to 4500 psig after each block of endurance cycling.

MoS_2 is effective in reducing abrasion of TFE fillers (B3, B35).

10.3 Scrapers

Scrapers are available which will exclude sand and dust better than MS28776M series scrapers without excessive rod wear.

The two most identifiable factors for scraper failure or reduced performance were curling of the cleaning edge away from the rod and diametral clearance due to thermal expansion. Candidates S1 and S15 definitely deformed during the test so that the cleaning edge curled away from the rod allowing contaminant to be drawn into the cavity between the scraper and the rod seal. A thermal expansion analysis of all candidates shows that S1, S2 and S9 had probable diametral clearance with the rod at 170°F which would allow contaminant to be drawn into the cavity between the scraper and the rod seal.

Significant design characteristics of a good scraper are:

- Stable configuration which does not warp, deflect, or twist at operating temperature.
- Positive seal on outer circumference of scraper.
- Interference fit on rod at operating temperature.

Scrapers which passed less contaminant than the MS28776M9 baseline were:

Candidate	Part Number	Manufacturer
S16	3534-00998-0122-0235	Greene, Tweed
S19	CEC5901-998-55	C. E. Conover
S7	120-218-1709	Dowty, Ltd.
S2	S32925-9P-19	W. S. Shamban
S17	TF1027-7214A	Tetrafluor, Inc.
S6	S-34-20	Hercules

Polyurethane and acetal plastic scrapers were not visually affected by 170° F ambient air, 250° F oil environment.

The bronze scrapers were more abrasive than any of the plastic scrapers.

10.4 Single Stage Rod Seals

The plastic seals had 70 times the leakage of the elastomer seals.

Conclusions on rod wear caused by the seal materials are shown under conclusions on seal materials (Section 6.1).

With the exception of candidate RS27 which failed, all elastomer seals had satisfactory leakage and wear performance.

10.5 Two Stage Rod Seals

- Semi-vented and unvented installations had less leakage than vented installations.
- Increase of O-ring cross section did not show longer life of cap strip than smaller cross section.
- Conventional cap strips are more likely to wear thru than a design which spreads the radial loading over more of the plastic seal such as the Shamban "Plus" seal or Greene-Tweed "Enercap". Also, the thickness of the plastic seal is usually greater on a Plus or Enercap type seal than a conventional cap strip.
- Differences in thickness of conventional cap strips between suppliers will make some more likely to wear thru than others.
- No problems were experienced with the unvented installations. The outboard seals did not appear to wear more rapidly due to lack of lubrication. Wear, when observed, was usually seen on inboard seals.
- Wear of the rod by the nylon backups on the "T" seal appears to increase with pressure.
- Two stage seals which performed with acceptable seal and rod wear and no leakage were:

  TRS21-SV - Redundant "Plus" seals with backups; material was proprietary/MoS_2 filled TFE; semi-vented installation.

  TRS4-SV - Redundant "trapezoid" seals; backup material was Revonoc 18158; semi-vented installation.

  TRS6-UV - Redundant O-rings with Revonoc 18158 backups; redundant backups on outboard seal; unvented installation.

  TRS20-UV - Redundant "Hat" seals; material was MoS_2 filled TFE; unvented installation.

10.6 Rod Bushing Material

When side loading is high, an aluminum bronze rod bushing will not prevent rod wear. However, the wear is reduced, and the resulting rod surface condition is better than when 17-4 PH material is used.

10.7 Long Life Test

Two stage rod seals significantly reduce leakage. None of the two stage rod seals leaked enough to measure during the entire test. All single stage rod seals but one (Candidate B35 with PNF O-ring) had total leakage varying from 2.45 to 217.2 ml.

From Table 13, comparing single stage rod seals only, it is significant to note that Candidate B35 and RS7 which have a form of backup loading into the rod, leaked much less than the Candidates B1 and B22 which did not have this feature.

No problems were encountered with unvented two stage rod seals.

There is no improvement in wear of rod with aluminum bronze end cap compared to 17-4 PH end cap.

MoS_2 added to backup material improves rod surface condition and reduces abnormal wear when backup material is abrasive.

11. RECOMMENDATIONS

11.1 Backup Rings

11.1.1 Relationships of Backup Performance to Backup Material Properties - For rectangular cross section, non cut backups it is suggested that there are trade offs between hardness and creep and shear strength and abrasiveness. Also, the coefficient of thermal expansion of the backup material can create clearances which completely cancel any beneficial effects of initial interference fit. There is a need for a program to systematically determine the ranges of values for backup materials which can be tolerated for maximum performance of the backup. Here, maximum performance is defined as complete protection of the O-ring with acceptable limits on backup wear and rod condition. The effect of thermal expansion could be treated by trial designs of backups with interference fit on the OD with the O-ring groove. Major problems to overcome would be possible accelerated wear of the backup on the ID and buckling of the backup at maximum operating temperature.

11.1.2 Statistical Determination of Backup Performance - A severe shortcoming in backup research in the last ten years has been the necessity of having to predict backup performance on the basis of one or two samples. In any system there are variations in results which are caused by tolerances in material properties, physical shapes, and an imperfect knowledge of all parameters affecting performance. There is a need for a program which subjects a reasonable statistical sample of each backup design to a controlled test to establish the mean and variance that may be expected of a backup ring for O-ring protection in excellent, good, fair, or poor categories. Tests on backup rings in the Dynamic Seals program suggest that even the best performing backups may have a predictable statistical variation in performance. This information, if known, would aid in reliability and maintainability analysis and predictions for hydraulic systems, and more importantly, serve as the basis for selection of backup rings. Standards such as unfilled TFE MS28774 and MS27595 should be used as baselines. The best performing candidates from the Dynamic Seals for Advanced Hydraulic Systems program and any others of merit should be included in the program. The use of automated test system which does not require the constant presence of a technician could keep program costs reasonable.

11.2 Scrapers

11.2.1 Establishment of a New Scraper Standard Design - In this program there were five scraper designs which transmitted less contaminant than the MS28776M baseline. Unfortunately, the five designs are not interchangeable in the same groove. The ability to change scraper designs without affecting groove requirements is important. Increased competition among suppliers for an application is desirable. Therefore, there is a need for a program which establishes a scraper groove to be promoted as a new standard and also performs tests on scrapers submitted by the seal industry which will allow modification of new designs and verification of effectiveness against solid and liquid contaminant.

11.3 Piston Seals

11.3.1 Dynamic Piston Seals for Advanced Hydraulic Systems - Just as with rod seals, there is controversy over what shape constitutes a long life piston seal. This effort would take the lessons learned in the Dynamic Seals program and apply them to piston seals. Wear of the cylinder barrel and tolerance of the seal to cylinder breathing would be two factors to evaluate. It would be interesting to see if backups such as the Shamban "Delta" design and the Fling trapezoid design perform as well when loading is radially outward instead of radially inward. Piston seal testing has been minimal at pressures above 3,000 psi. The Navy Lightweight Hydraulic Program concentrated on rod seal evaluation.

11.4 Rod Bushings

11.4.1 Rod Bushings for Long Life Actuator Designs - The Dynamic Seals program evaluated CRES steel and aluminum bronze as rod bushings. Overall, there was not much difference in rod wear other than the aluminum bronze did not promote rod damage by galling of the aluminum bronze as the CRES material did. The potential of finding a satisfactory metal or plastic is good providing the design techniques for successful use are developed along with the material. For example, there are many plastics which are promoted as bearing materials such as polyurethanes, nylon, Delrin and Vespel which may be good bushing materials but have coefficients of thermal expansion which create high diametral clearance. One way to promote use of such materials if they in fact reduce rod wear, is to explore interference fits of the plastic bushing in a metal end cap which would limit expansion of the plastic. Another way is to evaluate a wave spring loaded annular wedge which energizes the bushing radially inward to compensate for radial expansion with temperature. A "finger" design of bushing may be effective with very stiff materials such as Vespel SP21.

11.5 Gland Design

11.5.1 There are several important design details of MIL-G-5514 glands which greatly effect O-ring and backup life.

One detail which has been debated is the minimum squeeze required for O-ring installations. MIL-G-5514 squeeze values are lower than the percentages shown on Table I of MIL-G-5514 because factors such as O-ring stretch, eccentric installation of piston or rod, and eccentricity of groove to bore or piston OD are ignored. There is an upper limit on squeeze at which O-ring rolling and scrubbing begin. There is the possibility of a relationship of O-ring ID to stroke which is also a factor in O-ring rolling. The probability of spiral failure of O-rings is increased in long stroke applications, but the definition of "long stroke" is elusive. There appear to be no firm guidelines for fluid system designers. The Seals Panel of SAE A-6C Committee has held numerous discussions on a proposed revision to MIL-G-5514 which would ensure at least 5 percent squeeze under the most adverse tolerances. Most seem to favor such a revision, yet there is some apprehension over making the change without a test program. It is expected that the benefits of a 5 percent minimum squeeze design as compared to a design allowing a lesser squeeze would show up in low temperature tests.

Other details which often are overlooked, but effect performance are groove edge radius and slope of groove sides. MIL-G-5514 currently allows up to .010 radius or break on groove edges and up to 5° slope on sides. The large radius acts like increased diametral clearance to O-rings and backups. Several companies have adopted in-house design standards which require a much smaller groove corner radius or break. Yet there is currently no data available which would serve to convince the industry of the need for sharp groove corners. The high angle acts as a cam to feed backups into the rod when the seal is pressurized. This action is directly proportional to pressure.

There is a need for a program to review, and establish guidelines and design criteria which are firmly established by proper analysis and verification in realistic testing. This program would result in modifications to MIL-G-5514 which should significantly improve design practice.

APPENDIX A

COMPILATION OF USER INDUSTRY
SURVEY

1. Do you specify the rod seal to be used in an actuator or is the seal choice the recommendation of the actuator supplier.

We specify.	8
Supplier recommends	3
Both.	3

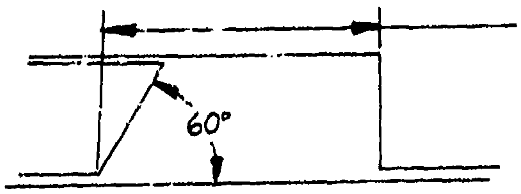
2. What rod seal groove design do you use on current production.

MIL-G-5514.	11	Some manufacturers use both
Modified MIL-G-5514	5	
Other	2	

3. If modified MIL-G-5514, what modifications are considered important.

a) "On light aircraft (Mod 206) the major diameter of the seal groove was increased to avoid increased squeeze of O-ring because of TFE cap strip thickness. As noted above, the Mod 206 is manual reversion. Increasing O-ring squeeze by the amount of cap strip thickness increases pilot effort of control which is objectionable."

b) "The Boeing-developed foot seal is used in the groove shown."



Std 2 backup ring width per MIL-G-5514. Diameters per MIL-G-5514. Two-Piece construction to allow for installation of the foot seal.

c) Flight control dual vented seals may be modified to meet installation of Shamban S12604 Double Delta Seal.

d) Corner radii in groove, squeeze.

e) "Modify groove depth and width to increase seal/groove occupancy to reduce seal displacement and associated wear under fully alternating pressure.

4. If "other" seal groove used, please identify.

a) A similar (see 3b) one piece integral groove was selected for O-ring seals with a triangular cross section backup ring for the X20A (Dyna-Soar).

b) None

c) Configured for flanged U-Seal, spring loaded type, graphite filled TFE.

d) Special groove for Omni or Cran Lip seals.

5. Do you use any rod gland bearings such as aluminum-bronze to reduce bushing wear.

aluminum bronze. 7
none 1

Other
i. Fabroid 2
ii. Dacron impregnated teflon on aluminum 1
iii. Aluminum. 1
iv. Torrington needle bearings (rotary actuator). 1
Filled TFE for "push-pull" type 1
v. Beryllium Copper. 2
(however one comment was that BeCu is no longer used)
vi. Aluminum-tin. 1

6. Which of the scrapers below have you used.

	No Experience	SERVICE EXPERIENCE * E	G	F	P
MS28776 Scraper	2	1/2	5-1/2		3
Shamban "Excluder"	7		2	1	1
C. E. Conover Scraper Ring	8	1	2	1	
MS 28903 Scraper	8				2
Other					
i. Equiflex					1
ii. Similar to MS 28776 of PTFE Material			1		
iii. Teflon			1		
iv. Master Pneumatic 529000-A			1		
v. Shamban S11665		1	1		
vi. "In distant past .. preferred felt wipers or boots. Scrapers tended to "score rods."					
vii. "BV design - similar to "Excluder" (predates Excluder)		1			

* Responses which indicate a range of two choices were scored as 1/2 for each choice.

7. (a) Have you run any tests to compare scrapers.

Yes. 4
No 9

(b) If so, which scraper was judged best.

i. "No advantage noted for either excluder forms - the other types we found totally unacceptable".

ii. "PTFE was used rather than metal to avoid rod wear due to dither cycling".

iii. "C. E. Conover - All other candidates failed"

iv. "Conover, BV Design Type"

v. Conover

(c) Did these tests include a sand and dust environment.

Yes. 3
No 1

8. (a) Have you had any recent experience with filled backup rings.

	SERVICE EXPERIENCE				
	NONE	E	G	F	P
Glass Filled	7	1	1		1
MoS_2	8			2	
Graphite Filled	9	1	1		
Bronze Filled	10				
Other					
i Carbon		1			
ii Virgin TFE				1	
iii Parker Parbak			1		
iv Turcon			1		

Comment on major problem using filled backup rings:

i "Extrusion on static seals - wear out on dynamic"
ii "None"
iii "Quality control"
iv "Our TFE seals are graphite filled. Glass filled were found to score sealing surface and had high friction.
v Not enough service experience to date on filled rings"
vi "Non evident to date".

(b) What elastomer seal/backup ring/TFE seal/scraper weakness do you see most often.

i) "Seal/Scraper - External foreign objects tend to imbed into scraper material resulting in scraper ring damage and increased rod end seal vulnerability to foreign object damage. Seal/Backup Ring - spiral failure on long stroke actuators (changed to "T" rings)."

ii) "Extrusion"

iii) "Installation problems with Double Delta, Plus, or any of the other forms of TFE capped O-rings in conjunction with closed glands per MIL-G-5514. Short life of seals in service, due to character of the helicopter flight loading, environment of operation and incapability of scrapers or excluders to cope with it".

iv) "The main problem with footseals and cap rings is that metal particles, mainly from within the PCU but also from the outside become imhedded in the teflon sealing surface where they act to score the chrome plated piston rods. This results in corrosion of the base metal and the relatively high nuisance leakage rates. There had been some thought that single stage seals were less prone to this problem, but service records indicate it occurs equally on both single stage and two stage seal units."

v) "Seal - potential for rolling/spiral failure. Backup ring - failure of MIL-STD to fit without trimming. TFE seal-potential for leakage. Scraper - No weakness noted in our application."

vi) "O-ring extrusion. Cap seal leakage."

vii) "Seal leakage due to quality problems."

viii) "Failure to exclude dirt from sealing elements."

ix) The only elastomer that we consider adequate for -65 to +275 degrees F in hydraulic systems is fluorosilicone. Unsatisfactory for dynamic seal but OK for static. Nitrile permanent set is excessive at high temp. causing subsequent leakage at low temperature. On cap strip seals fluorosilicone require more squeeze for adequate loading of teflon."

x) "Seal creep on seals. Scrapers pick up abrasive materials and score rod, which leads to rod seal failure. Installation problems on small size Omni type seals w/o special gland design. TFE seals tend to seep at low pressure (cap type seals). Split backup rings don't always fit properly."

xi) "Life limitations of TFE/O-ring seals due to helicopter alternating load - high cycle environment."

xii) "Spiral failure - large sizes, installation damage."

9. On the following matrix indicate your service experience with each element listed.

COMPILATION OF AIRFRAME MANUFACTURER SURVEY

	IDENTIFY AIRCRAFT	FLUID	TYPE OF ACTUATOR	SYSTEM TEMP. MIN. °F	SYSTEM TEMP. MAX. °F	PERFORM
T Seal	E3A	MIL-H-5606	UT	-65	160	G (22)
	A10A	MIL-H-5606	UT, E	-40	225	G
	DC4,DC9,DC10	MIL-H-5606	SHOCK STRUTS	-65	160	E
	(30)	MIL-H-5606	PC,UT	-65	160/275	G to E
	F14	MIL-H-5606	PC,UT,EM	-65	27[illegible]	F
	F4	MIL-H-5606	PC,UT,RESV	-45	225	G
	CH46,CH47	MIL-H-5606	UT,LAT DAMP OLEOS	-65	+220	E
	XFV-12	MIL-H-83232	PC	-40	+275	G
	C130,C5A	MIL-H-5606	PC,UT	-65	200	E
	F111 (F16)	MIL-H-5606	PC,UT	-65(-40)	275	G
MS28775 O-ring/ Triangle backup	X-20A	MLO 7277 (1)	PC	+20	400 (2)	E (3)
	SST	WS7597 (4)	PC	-50	400	E (5)
	F4	MIL-H-5606	PC, UT	-40	225	G
	F111	MIL-H-5606	PC, UT	-65	275	P (6)
Cap Strips	CH46,CH47	MIL-H-5606	FLT CONT	-65	+220	G
	RA5C,T-2C, XFV-12A	MIL-H-5606 (83282)	PC,UT	-65(-40)	+275	G
	A10A	MIL-H-5606	PC	-40	275	F
(TFE slipper)	DC9,DC10	Skydrol	PC,UT	-65	225	G
(Double Delta)	(7)	MIL-H-5606	PC	-65	160°/275°F	F
	CH 53	MIL-H-5606	PC	-65	275	F-Rod P-Piston
(channel type)	707,727, 737	BMS 3-11 (8)	PC (9)	-50	225	G (10)
	E2,A6,F14	MIL-H-5606	PC,UT	-65	275	F
	F14A	MIL-H-5606	PC	-65	275	F
	F111	MIL-H-5606	PC	-65	275	G (11)
	F16	MIL-H-5606	PC	-40	275	G (11)
	F14 Radar	MIL-H-5606	Rotary	-65	275	- (12)

COMPILATION OF AIRFRAME MANUFACTURER SURVEY - CONTINUED

	IDENTIFY AIRCRAFT	FLUID	TYPE OF ACTUATOR	SYSTEM TEMP. MIN. °F	SYSTEM TEMP. MAX. °F	PERFORM
Foot Seal	Test Only (14)	Skydrol		-40	225	G (13)
		MIL-H-5606	PC, UT	-65	275	P
	707,727, 737,747	BMS 3-11	PC	-50	225	G (10)
Plus Seal	Test Only	MIL-H-5606	Flt Cont	Room Ambient		P
	DC8 (15)	Skydrol	PC, UT	-65	225	P
		MIL-H-5606	PC	-65	160° 275° F	F
	F4	MIL-H-5606	Damper	-40	225	G
Spring Energized TFE "C" Seal (Ex. Bal or Omni)	Test Only	MIL-H-5606	Flt Cont	Room Ambient		F
	F14	MIL-H-5606	Em	-65	275	F
	C141,C5A (16)	MIL-H-5606	PC, UT	-65	240	E
	F14 and F15 Radar	MIL-H-5606	Rotary	-65	275	E
	CH53E, CH53A/D	MIL-H-5606	PC, Reservoir	-65	275	G
MS28775 O-ring/	S76,CH53E	MIL-H-5606(17)	PC	-65	275	(25)
	DC8, DC9, DC10	Skydrol	UT	-65	225	G
	Mod 214A11	MIL-H-5606	PC	-65	275	P

COMPILATION OF AIRFRAME MANUFACTURER SURVEY - CONTINUED

	IDENTIFY AIRCRAFT	FLUID	TYPE OF ACTUATOR	SYSTEM TEMP. MIN. °F	MAX. °F	PERFORM
MS28775 O-ring/ MS28774 backup	CH46,CH47	MIL-H-5606	Utility	-65	+275	G (29)
	S61, S58	MIL-H-5606	All	-65	160	G (26)
	A10A	MIL-H-5606	UT,EM	-40	275	G
	Mcd 214 All	MIL-H-5606	PC	-65	275	P (18)
	E2,A6, EA6B, F14	MIL-H-5606	PC,UT,EM	-65	275	F to G
	F14A	MIL-H-5606	PC	-65	275	G
	F4	MIL-H-5606	PC,UT	-40	225	G
	F111	MIL-H-5606	PC,UT	-65	275	G
	F16	MIL-H-5606	PC,UT	-40	275	G
	C130,C141 C5A	MIL-H-5606	PC,UT	-65	200	F
	CH53	MIL-H-5606	UT	-65	275	F (27)
	RA5C T-22 (XFV-12)	MIL-H-5606 (83282)	PC,UT	-65(-40)	225	G
Two Stage (20 Vented Seal	CH46,CH47	MIL-H-5606	PC,LAG Dampers	-65	+220	E
	CH47	MIL-H-5606	PC	-65	+220	E
	DC10	Skydrol	PC	-65	225	E
	R&D	MIL-H-5606	--	-65	275	G
	707,727 747	BMS 3-11	PC	-50	225	G
	C5A (19)	MIL-H-5606	PC	-65	200	G
	F14 & F15 Radar (20)	MIL-H-5606	Rotary	-65	275	E
(28)	CH53E	MIL-H-5606	PC	-65	275	E
(28)	Lamps, S76 UTIAS	MIL-H-83282	PC	-65	275	E
	A10A	MIL-H-5606	UT	-40	275	G

COMPILATION OF AIRFRAME MANUFACTURER SURVEY - CONTINUED

	IDENTIFY AIRCRAFT	FLUID	TYPE OF ACTUATOR	SYSTEM TEMP. MIN. °F	SYSTEM TEMP. MAX. °F	PERFORM
Two Stage (2C Vented Seal (Continued)	DC8, DC9, DC10	MIL-H-5606	LG Shock Strut	-65	160	E
	(21)	MIL-H-5606	PC, UT		160 and 275°F	G to E
	E3A	MIL-H-5606	UT	-65	160	G
	F14	MIL-H-5606	PC,UT	-65	275	E
	F4	MIL-H-5606	(23)	-40	225	G
	F111	MIL-H-5606	UT	-65	275	G
	F16	MIL-H-5606	UT	-40	275	G
	C130 C5	MIL-H-5606	UT (large)	-65	200	E
	XFV-12	MIL-H-83282	PC	-40	+225	G
MS28775 O-ring/ glass filled backup	(24) CH53E	MIL-H-5606	UT	-65	275	(25)

NOTES:

1. MLO-7277: Super-refined petroleum fluid.
2. The X20A system was designed to limit fluid temperature to 400°F, but the seals [illegible] required to operate at 550°F to provide a safety margin.
3. Program cancelled prior to first flight. Seals and actuators perform[illegible] in [illegible] tests and on iron bird used many years at AFFDL.
4. WS-7597: Humble Oil trimethylolpropane ester fluid.
5. Lab experience very good. Program cancelled prior to flight.
6. Usage was abandoned early in program due to installation difficulties o[illegible] backup. Extrusion of triangular backup was also a problem.
7. Mod 47 all, Mod 204B, UH-1A, UH-1B, UH-1C, UH-1D, UH-1E, UH-1F, HH-1K, [illegible], AH-1J, AH-1S, AH-1T, Mod 222, Mod 301, Mod 212, Mod 309, Mod 409, Mod 214A, Mod 214B, Mod 214C, Mod 214ST, UH-1N.
8. BMS 3-11: Boeing spec for phosphate ester fluid.
9. Channel seals used in actuators with manual reversion mode (to reduce friction).
10. Channel seals and foot seals provide long life but are also subject to nuisance leakage.

COMPILATION OF AIRFRAME MANUFACTURER SURVEY - CONTINUED

NOTES: Continued

11. Used only on input stage of flt control system actuators.
12. Superceded by "U" seal spring loaded teflon.
13. Normally requires split gland for instability.
14. Shamban version of foot seal - AH-63, replaced by Double Delta in rod seal application due to high force.
15. 206A, OH 58A, 206L, 206L-1; rod application only.
16. Piston seals only (not rod end seals).
17. For Skydrol, it is assumed this report really is for EPR O-rings, not MS28775.
18. Non-cut backup piston appl, rating is good when mod by notching OD of backup
19. S12604 Double Delta
20. "U" seal is second stage seal-vented to return pressure.
21. Piston head only - Mod 206A, OH58A, 206L, 206L-1. In addition, all other aircraft are being so fitted thru attrition of cap type piston seals.
22. Limited experience only. Installed in hope of reducing leakage on these long stroke actuators.
23. PC, UT, Reservoir.
24. Would expect metal wear problems with glass filled, based on our experience with rotary actuators.
25. Not enough experience.
26. 1500 psi system.
27. 3000 psi system
28. This data is for 2 stage non-vented rod seals.
29. Except low temperature.
30. Piston head only on Bell Mod 206A, OH58A, 206L, 206L-1

COMPILATION OF AIRLINE INDUSTRY SURVEY

(Based on three out of three contacted)

1. On the following matrix, indicate your service experience with the performance of the following as rod seals.

	IDENTIFY AIRCRAFT	FLUID	TYPE OF ACTUATOR	SYSTEM TEMP. MIN. °F	SYSTEM TEMP. MAX. °F	PERFORM
Cap Strip	L1011	Skydrol 500B	PC	-65	200	F
	727	Skydrol	All	-65	180	P
	707-727	Skydrol	UT	-65	200	G
Channel Seal	All Fleet Acft	Skydrol	UT	-65	200	G
	727	Skydrol	All	-65	180	E
	L1011, DC9 B727, DC8	Skydrol	PC	-65	160	G
Foot Seal	727	Skydrol	PC	-65	200	E
	727	Skydrol	UT & Sec. PC	-65	180	G
	DC8, B727	Skydrol	PC, UT	-65	160	F
Plus Seal	--	--	--	--	--	-

COMPILATION OF AIRLINE INDUSTRY SURVEY - CONTINUED

	IDENTIFY AIRCRAFT	FLUID	TYPE OF ACTUATOR	SYSTEM TEMP. MIN. °F	SYSTEM TEMP. MAX. °F	PERFORM
NAS164/MS27595	All Fleet Acft	Skydrol	PC, UT	-65	200	G
Backup	DC8	Skydrol	UT	-65	160	P
NAS 1611/MS28774	707	Skydrol	PC, UT	-65	200	G
Backup	727	Skydrol	UT	-65	180	G
Two Stage Vented Seal	727	Skydrol	PC	-65	180	E
"T" Seal	L1011	Skydrol	UT	-65	200	F
	L1011	Skydrol	UT	-65	160	P
	727	Skydrol	All	-65	180	E
Glass Filled Backups/ with NAS1611 O-rings	--	--	--	--	--	-
TFE "C" Seal/Spring Energ. (ex: Bal. Seal, Omni Seal)	L1011	Skydrol	PC	-65	200	P

2. If a two stage vented seal was used what was the configuration. Three were indicated as being used.

   (a) O-ring w/channel seal 1st stage and 2nd stage.
   (b) TFE ring 1st stage; O-ring w/channel seal 2nd stage.
   (c) O-ring w/channel seal 1st stage; O-ring w/backup 2nd stage.

3. What scrapers have you used

	PERFORMANCE *			
	E	G	F	P
MS28776 scraper.......metal.	1/2	1/2	-	1
non-metal. . . .	1/2	1-1/2	-	-
W. S. Shamban "Excluder"	-	-	-	-
MS28903 Scraper.	-	-	-	-
Other: Shamban S11065	-	-	1	-

4. What elastomer seal/backup ring/TFE seal/scraper weakness do you see most often in rod seal applications

   (a) No significant problems.
   (b) Rolling of the elastomeric seal (including T-seal). Wear of TFE seal (in many applications we use "Turcon" type seals to help in the wear area.
   (c) Steel particles imbedded in teflon causes scratches on piston. Poor fit of backup ring and scraper (excessive end gap). Poor wear resistance.

5. How much difficulty do you have with actuator rejections due to rod seal leakage just after start-up on cold mornings

   Negligible 2, Moderate 1, Much 0

   Comment:

   (a) Mechanics frequently apply heat to actuators in local area of seals to stop leaks.
   (b) "L1011 components with Tee-rings give most problem. We believe this is due to inadequate squeeze in design of assembly".

6. When rod seal leakage reaches a level to be declared a failure, do you find that it is generally a wear out situation (W) or a failure at a point far short of expected life (F)

   W.............. 2
   F.............. 1

7. Indicate nature of failures noted at overhaul after rejection. (check as many as applicable).

Leakage...............................	3
Elastomer extrusion/wear.............	2
Permanent set of O-rings.............	1
Rod wear..............................	0
Gland bore wear.......................	1
Seal rolling..........................	1
Other....... O-ring nibble...........	1

* Responses which indicate a range of two choices was scored as 1/2 for each choice.

8. Do you impose specific requirements on aircraft manufacturer(s) with regard to the following:

	Y	N
O-ring compound....................................	1[1]	1
O-ring squeeze.....................................		2
Backup rings......................................		2[2]
TFE Seals..		2
Scrapers...		2
Rod Material/coating...............................		2
Housing material/coating...........................		2
Two stage vented rod seals.........................		2

Comments: Commercial aircraft specifications rarely go to this detail level.

9. Do you do any testing on your own to determine satisfactory improvements/performance for:

	Y	N
Rod seals..	2[3]	1[4]
Scrapers...		2[4]
Backup rings......................................		2[4]
Rod Surface Coating................................		2[4]
Elastomer compound for O-rings.....................	1[3]	2[4]

NOTES:

1. Require use of EPR material in Skydrol systems.
2. Prefer use of continuous (non-cut) backups where possible.
3. Service evaluation.
4. Generally no - however in problem areas we do not change seal configurations, material, etc. to resolve problem.

APPENDIX B

DSAHS-10

PRELIMINARY
SPECIFICATION ON DESIGN PRACTICE FOR ROD SEALS
USED IN FLY-BY-WIRE
FLIGHT CONTROL ACTUATORS

Contract F33615-78-C-2027
Project 3145

Prepared for:
Air Force
Wright Aeronautical Laboratories
Wright Patterson Air Force Base, Ohio

1.0 SCOPE

This document addresses design practice for rod seals intended for use in Fly-By-Wire (FBW) Flight Control System actuators on Class 3000 psi, Type II (-65 to +275°F) hydraulic systems in accordance with MIL-H-5440 using MIL-H-5606 hydraulic fluid.

2.0 APPLICABLE DOCUMENTS

The following documents form a part of this document to the extent specified herein.

2.1 SPECIFICATIONS

Military

MIL-H-5440	Hydraulic Systems, Aircraft, Types I and II, Design and Installation Requirements for.
MIL-H-5606	Hydraulic Fluid, Petroleum Base; Aircraft, Missile and Ordnance.
MIL-G-5514	Gland Designs; Packings, Hydraulic, General Requirements for

3.0 REQUIREMENTS

3.1 GENERAL

The design practices and sealing devices described herein have shown in tests to provide low leakage and acceptable rod wear for at least 14 months equivalent service in a Fly-By-Wire Flight Control Actuator. Some sealing devices or practices are identified which will provide acceptable performance up to 60 months service if oil temperatures are controlled to maximize elastomer life.

3.2 SEAL MATERIAL

Elastomers - Use of elastomers meeting MIL-P-83461 is recommended.

Plastics - The materials below are listed in relative order of increasing abrasiveness on hard chrome plate. Materials at the top of the list are non-abrasive but wear at a higher rate than those lower in the list.

Unfilled TFE
Polyimide with inorganic filler (Revonoc 18158)
TFE blend (Revonoc 6200)
Acetal Resin (Delrin, Celcon)
TFE with polymeric filler (Tetralon 720)
TFE with proprietary filler (Shamban Compound 20)
Turcon with MoS_2 filler (Shamban Compound 99)
Turcon with proprietary/MoS_2 filler (Shamban Compound 19)
Turcon with proprietary filler (Shamban Compound 18)
Nylon
Polyimide SP-1, SP-21

Avoid the use of bronze filled TFE.

3.3 GLAND DESIGN

3.3.1 Design Practice to Increase Seal Life

Adjust dimensions and tolerances of specification MIL-G-5514 glands so that O-ring squeeze is not less than 5 percent when all adverse conditions are considered. Calculation of squeeze must consider reduction in O-ring cross section due to stretch, eccentricity of rod or piston in bore, and eccentricity of groove with respect to land.

The gland depth should not be less than the maximum cross section of the backup ring at 70°F.

Reduction of diametral clearance from the maximum allowed in MIL-G-5514 will aid in control of squeeze and will increase seal life.

Reduce groove edge radius to .002 +.005/-.000. The smaller radius will reduce backup ring extrusion.

Consider roll resistant seal configurations in place of O-ring in MIL-G-5514 glands when the ratio of actuator stroke to O-ring ID is high. Various sources indicate spiral failure of O-rings when stroke exceeded 12 inches.

3.3.2 Design Practice Which Reduces Seal Life are:

- Use of a static O-ring size in a dynamic application.
- Reduction of squeeze to reduce friction.
- Use of no backup width grooves for "T" seals with resultant thin backups.
- Use of diametral clearances in excess of those allowed by MIL-G-5514.

3.4 ENDURANCE SPECTRUM

The endurance spectrum below is the minimum for seal qualification. The spectrum should be modified by additional cycles in the appropriate percentage strokes and external loading conditions if structural endurance requirements exceed those listed below. For each one thousand hours of aircraft life the spectrum below should be imposed.

Percent of Total Stroke	Cycles
1.0	9.05×10^6
2.0	8.75×10^5
10.0	6.25×10^4
50.0	1.00×10^4
100.0	2.50×10^3
	10.00×10^6

3.5 LEAKAGE

Leakage requirements may be set according to type of rod seal. Typical values for seals installed in -214 gland are as follows:

Seal Type	Typical Nominal Leakage in 1×10^7 Cycles of Endurance Spectrum - ml
Single Stage Plastic	48
Single Stage Rubber	6
Two Stage Unvented (Regardless of seal material)	0.5

The above typical leakage values will increase if rod size increases or if number of 50 or 100 percent stroke cycles increase. For minimum leakage and longest life, two stage rod seals should be specified.

3.6 SINGLE STAGE SEALS

3.6.1 O-Ring and Backup.

Backup design characteristics which improve performance are:

Shape - Backups which form an included angle of approximately 60° with the rod on the face toward the backup reduce the probability of O-ring extrusion.

Staging - When extrusion protection is not required on both sides of the O-ring, placing two rectangular backups on the atmospheric side of the O-ring will reduce the probability of O-ring extrusion.

Material Properties - Extremely hard (Rockwell R118, E51) materials should be avoided. Unfilled TFE with a hardness of Rockwell R58 or proprietary materials with a similar low hardness cold flow offer good short term protection but can exhibit high wear over long term service. Materials with hardness between these two extremes should be selected.

Configuration - Backups should be non-cut and have light initial interference with the rod. This will maintain the backup contact with the rod to reduce probability of O-ring extrusion until the material has enough cold flow to maintain rod contact.

3.6.2 Plastic Cap Seals.

Conventional cap seals must have adequate thickness to prevent wear-through under the O-ring. Cap seals which distribute the radial force from a special elastomer shape over a greater area resist wearing through.

Use of a no backup width cap seal in conjunction with two rectangular backups extends the life of the cap seal. If pressure occurs only in one direction, place both backups on the atmospheric side of the cap seal.

3.7 TWO STAGE SEALS

Types of two stage seal installations are:

Unvented - The cavity between seals is not vented to atmosphere or return.

Semi-Vented - The cavity between seals is vented to the cylinder retract port thru a check valve.

Vented - The cavity between seals is vented to system return pressure.

All three types of installation are acceptable, however the unvented installation is recommended because it occupies the least space, potentially will leak less, and is lower cost to manufacture than the other two installations.

When designing an actuator with two stage unvented seals, the inboard seal should have protection against extrusion in both directions. Also, the friction of both seals when pressurized to system pressure should be included in opposing loads to cylinder motion in both directions.

For all three types of installation it is desirable to have a small groove whose volume is not less than one quarter that of the seal gland between the inboard and outboard seal grooves to trap the normal seal wear particles given off.

Examples of two stage rod seals which have given excellent performance in 1-inch diameter rod seal tests are shown on Figure 1.

3.8 SCRAPERS OR EXCLUSION DEVICES

Materials - The material should have a high bending modulus. Acetal resin plastic and some filled TFE compounds are acceptable.

Configuration - The scraper should be supported on the rod on both the inboard and the outboard side to resist deformation. Some materials such as acetal resin with adequate cross section are stiff enough without support at both edges. Loading of the scraper into the rod is desirable by use of an elastomer or by use of a high modulus material with an interference fit on the rod at maximum operating temperature. The elastomer also may act as a dust seal for the outer diameter of the scraper.

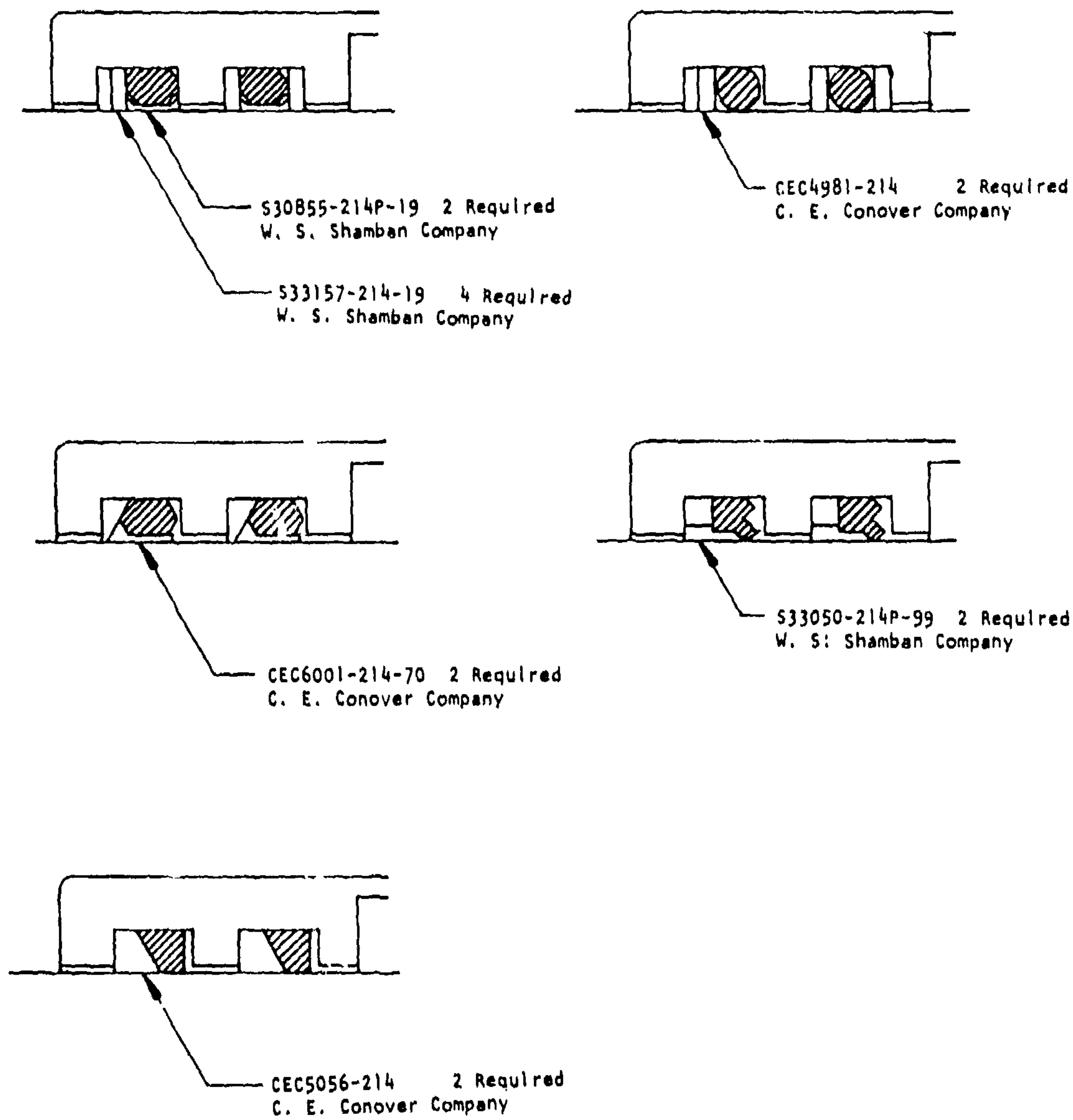


FIGURE 1

Examples of High Performance Two Stage Rod Seals

APPENDIX C

COMPARISON OF BACKUP RING SCREENING TEST RESULTS WITH SELECTED PROGRAMS

Much data on backup ring performance has been generated by recent programs. Where possible, a comparison by material and shape was made. Test conditions vary from program to program, but since each effort was to test the backup to its extremes, a good performer for one program may indicate a potential candidate for a future program. There was fair concurrence among programs which had rod cycling as part of the test. Concurrence was poor if the program had impulse testing only.

Table 1 presents the comparison of backup results for several selected programs and is by no means exhaustive. References cited in Table 1 are as follows:

1. "Long Life Elastomeric Hydraulic Seals", Air Force Materials Laboratory, AFML-TR-73-90, Part I, Parker Hannifin Corp., 1973.

2. "Long Life Elastomeric Aircraft Hydraulic Seals", Air Force Materials Laboratory, AFML-TR-77-194, Parker Hannifin Corp., 1977.

3. "High Performance Hydraulic Sealing Systems", Air Force Materials Laboratory, AFML-TR-72-91, Part VI, Versar, Inc., 1972.

4. "Lightweight Hydraulic System Rod Seal Study", Naval Air Systems Command, 2-51700-C/9R-52140, Vought Corporation, 1979.

5. "Hydraulic System Seal Development", AVRADCOM, USAAVRADCOM TR-81-D-17, Vought Corporation, 1981.

6. "Endurance Tests of Hydraulic Packings in a Large-Bore Long-Stroke Cylinder at 275°F", NA-55-1136 (Contract AF33(600)-27787), North American Aviation, Inc., 1955.

7. "Endurance Tests of Hydraulic Packings in a Large-Bore Long-Stroke Cylinder at Temperatures Ranging from -65°F to 300°F", NA-56-105 (Contract AF33 (600)-27787), North American Aviation, Inc., 1956.

TABLE 1. COMPARISON OF BACKUP RING SCREENING RESULTS WITH OTHER PROGRAMS

REF	BACKUP DESCRIPTION	TEST CONDITIONS	RESULTS	SIMILAR TO	COMMENT
[1]	Rectangular, unfilled TFE material	150000 cycles; 3000 psi; MIL-H-5606; 275°F	Little or no damage to seal, backup was worn	B1	Concur, except failure rate is increased when test includes impulse pressure.
	Rectangular, glass/ MoS_2 filled TFE material.		Backup extrusion was limited; O-ring was scratched; no rod damage occurred.	B21	Concur, except glass/MoS_2 filler gave moderate rod wear
	Rectangular, noncut, polyimide material		Failed after 34200 cycles. Apparently "... due to the rubbing of the seal against the hard polyimide".	B15	Concur. In our tests failure was imminent.
	Two stage, polyimide Outer backup, Tetralon 720 inner backup		Successfully completed tests	B19	Concur. Some O-ring nibbling occurred.
[2]	Two stage Revonoc 18158 material.	100000 cycles; 50/4000 psi; 350°F MIL-H-83282	Very little extrusion of backups. One of three samples failed.	B22	Concur. We had no failures. O-ring protection was excellent to good.

TABLE 1. CONTINUED

REF	BACKUP DESCRIPTION	TEST CONDITIONS	RESULTS	SIMILAR TO	COMMENT
[2] Contd	Single stage Revonoc 18158 material	149000 cycles; 50/4000 psi; 350°F MIL-H-83282	Successfully completed test. Only slight extrusion to backups.	B4	Concur. Some O-ring nibbling occurred.
[3]	Triangular shape Vespel SP-21 material	9000 cycles of 0-5700 psi impulse pressure 400°F, MIL-H-83282A fluid. Diametral clearance equals .018	"Results were quite good. A loss of only 0.5 ml hydraulic fluid occurred over the 5 hour run, and all seals appeared like new after the test".	B27	B27 failed after only 1.49 x 10^6 endurance cycles plus 6100 impulse cycles due to nibbling and extrusion of the O-ring
	Rectangular shape, Vespel SP-1 material		Survived test with no leakage	B15	B15 allowed O-ring nibbling to the point failure was imminent after 226077 endurance cycles plus 5604 impulse cycles
	Rectangular shape, Vespel SP-21 material		Survived test with no leakage	B25	B25 completed 3.37 x 10^6 endurance plus 111014 impulse cycles. Leakage occurred and the O-ring was in poor condition

TABLE 1. CONTINUED

REF	BACKUP DESCRIPTION	TEST CONDITIONS	RESULTS	SIMILAR TO	COMMENT
[3] Contd	Rectangular shape, Revonoc 18158 material		Two of four samples failed approximately half way thru the test. The two remaining samples survived with only 1 drop and 10 ml leakage respectively.	B4	B4 completed our screening test. The O-ring had some nibbling on the ID and OD.
[4]	Two stage Revonoc 18158 material	8000 psi, -40°F to +275°F, MIL-H-83282 fluid 400 hr of cycling 90 percent at ±1.75 inch; 10 percent at ±0.10 inch	Completed the test. Seals looked like new. No noticeable leakage.	B22	Concur
[5]	Trapezoid shape, Revonoc 6200 material Inboard seal of a two stage rod seal installation.	3000/80000 psi; -25 to 275°F; MIL-H-5606/MIL-H-83282; 5 x 10^6 cycle endurance plus 20 x 10^6 cycle rotor feedback	"The O-ring was in very good condition with no nibbling. The trapezoid backup ring was in very good condition with no visible wear particles This seal survived the entire test." "Zero leakage during test".	B29	Conocur. Only light nibbling occurred in screening test.

TABLE 1. CONTINUED

REF	BACKUP DESCRIPTION	TEST CONDITIONS	RESULTS	SIMILAR TO	COMMENT
[6]	Single Turn Lockheed "Delta" shape Teflon material	3000 psi, 275°F, MIL-C-5606 fluid -218 size rod seal application 2000 cycles, 15.9 in stroke.	"...after...[3000]... cycles the backups were considerably worn ... causing leakage from the cylinder end." Diametral clearance was .0078 at 275°F.	B3,B23, B30, B35	As a filled material backup, this configuration has consistently given excellent O-ring protection
[7]	Single turn wide shape unfilled TFE material		"...excessive and uneven wear on the inner periphery...ultimate packing failure..." Diametral clearance was .0041.	B5,B17	B5 and B17 survived the screening tests but nibbling and extrusion of the O-ring occurred with both candidates.
	"NAA designed Plano-concave single turn Teflon rings"		Performed satisfactorily in piston application but failed after 13000 cycles of the rod seal application test temperature was 300°F. Diametral clearance was .0064.	B10	B10 completed the screening test with little wear and 4 drops leakage. The O-ring was nibbled on the ID.

*U.S.Government Printing Office: 1982 — 559-003/2021